# Adaptive Control for Active Distribution Networks

**Thipnatee Sansawatt**

**(Punim)**

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# Abstract

Rise of the global environmental awareness and climate change impacts caused by greenhouse gases emissions brings about a revolution in the power and energy industries to reduce fossil fuels and promote low-carbon and renewable distributed generation (DG). The new dimensions, mainly encouraged by the governments' legislative targets and incentives, have allowed the development of DG worldwide.

In the U.K., renewable DG especially wind is being connected on distribution networks and ranges widely in scales. Despite the growing number of potential DG sites, the surplus generation present on the passive networks can lead to some technical problems. In particular, rural networks where wind farms exist are prone to voltage rise and line thermal constraints. In order to accommodate new DG and ensure security of supply and network reliability, active management to mitigate these issues are required. In addition, the duties to provide cost-effective DG connections at avoided expensive investment incurred from conventional solutions, e.g., reinforcement and maintain robust network are a major challenge for Distribution Network Operators (DNOs).

This thesis endeavours to develop an adaptive control scheme that provides local and real-time management against voltage variations and line capacity overload at the point of wind connections on rural distribution networks. Taking into account maximising power exports and providing an economically-viable control scheme, the wind turbine's capability, comprising reactive power control and active power curtailment, is used. Whilst the thesis concentrates on the decentralised control applying several different algorithms, in addition, semi-coordinated and centralised approaches that adopt on-load tap changing transformers' regulation and Optimal Power Flow tool are developed. Comparisons of these approaches based upon measures, i.e., economics, DG penetration and performance are determined. As an outcome, the developed scheme can enable growing integration of renewable DG on distribution networks and can be seen as an interim solution for the DNOs towards Smart Distribution Networks.

# Acknowledgements

First and foremost, I wish to convey my greatest gratitude with truthfulness to my supervisor, Professor Gareth Harrison, for every moment of his time given to me with helpfulness, knowledge, guidance, encouragements, inspirations and humours while (conducting the MSc dissertation and onto) pursuing this PhD, which are invaluable experiences in my life. Without your support, my PhD and this thesis would not have been achieved.

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Finally, big thanks belong to my close friends in Thailand and to my dearest friend, Donut, for always caring, encouraging and listening to all my voices.

# Declaration

I, Thipnatee Sansawatt (Punim), declare that this thesis has been written by myself. The research contents and the results presented within are my own unless otherwise referenced or stated. The work has not been submitted for any other degree or professional qualification.

The publications included at the end of this thesis were the main collaborations between Prof. Gareth Harrison, Dr Luis Ochoa and myself.

The technical report referenced in Section 1.5 of Chapter 1 with the summary presented in the Appendix was an outcome of my industrial internship during January to February 2010 at Technology Centre, E.ON Engineering (now E.ON New Build & Technology Limited). The project was under a supervision of Dr Ting Ma.

Signed:

Date:

"Your time is limited, so don't waste it living someone else's life. Don't be trapped by dogma - which is living with the results of other people's thinking. Don't let the noise of others' opinions drown out your own inner voice. And most important, have the courage to follow your heart and intuition. They somehow already know what you truly want to become. Everything else is secondary"

"Stay Hungry. Stay Foolish."

**Steve Jobs**

**(1955 – 2011)**

**Stanford University, California, 2005**

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# Abbreviations

| | |
|---|---|
| AMI | Advanced Metering Infrastructure |
| ANM | Active Network Management |
| APFC | Automatic Power Factor Control |
| AuRA-NMS | Autonomous Regional Active Network Management System |
| AVC | Automatic Voltage Control |
| AVPFC | Automatic Voltage Power Factor Control |
| AVR | Automatic Voltage Regulator |
| AVRS | Automatic Voltage Reference Setting |
| BIPV | Building-Integrated Photovoltaic |
| CAPEX | Capital Expenditure |
| CCS | Carbon Capture and Storage |
| CHP | Combined Heat and Power |
| $CO_2$ | Carbon Dioxide |
| DECC | Department of Energy and Climate Change |
| DFIG | Doubly-Fed Induction Generator |
| DMS | Distribution Management System |
| DNO | Distribution Network Operator |
| DG | Distributed Generation |
| DUoS | Distribution Use of System |
| EHV | Extra High Voltage |
| EMEC | European Marine Energy Centre |
| ENA | Energy Network Association |
| ENSG | Electricity Network Strategy Group |
| ESQCR | Electricity Safety, Quality and Continuity Regulations |
| FG | Firm Generation |
| FITs | Feed-in Tariffs |
| GW | Gigawatt |
| HV | High Voltage |
| Hz | Hertz |
| IES | Institute for Energy Systems |
| IIS | Interruptions Incentive Scheme |

| | |
|---|---|
| kW | Kilowatt |
| kWh | Kilowatt-hour |
| LCBP | Low Carbon Buildings Programme |
| LCNF | Low Carbon Network Fund |
| LIFO | Last-In-First-Off |
| LV | Low Voltage |
| MCT | Marine Current Turbines |
| MV | Medium Voltage |
| MW | Megawatt |
| MWh | Megawatt-hour |
| NFG | Non-Firm Generation |
| NPV | Net Present Value |
| Ofgem | Office of the Gas and Electricity Markets |
| OLTC | On-Load Tap Changing |
| O&M | Operation and Maintenance |
| OOP | Object-Oriented Programming |
| OPEX | Operational Expenditure |
| OPF | Optimal Power Flow |
| OW | Operational Windows |
| PFC | Power Factor Control |
| PFCVC | Power Factor Control Voltage Control |
| PSD | Passive Solar Design |
| PV | Photovoltaic |
| R&D | Research and Development |
| RNFG | Regulated-Non-Firm Generation |
| RO | Renewables Obligation |
| ROS | Renewables Obligation (Scotland) |
| ROC | Renewables Obligation Certificate |
| RTU | Remote Terminal Unit |
| SCADA | Supervisory Control and Data Acquisition |
| T Mgt | Thermal Management |
| UoS | Use of System |
| VPP | Virtual Power Plant |
| V Mgt | Voltage Management |
| V&T Mgt | Voltage and Thermal Management |

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# Chapter 1

# Introduction

## 1.1 Thesis Background

In an attempt to reduce carbon dioxide emissions, the UK Government is committed to increasing the share of energy from renewable sources to 15% in 2020 [1]. This implies 30% of electricity to be produced from renewables. The decision has significantly influenced a transition in the power industry to discourage fossil fuel consumption and motivate the connection of low-carbon and renewable distributed generation (DG) into distribution networks. With this, substantial amounts of funds and incentives are being rolled out as a means to support the development in DG technologies. Consequently, there has been a rapid growth in DG (especially wind farms) in the regions possessing rich wind resources.

Notwithstanding a large capacity of DG in the distribution networks, traditional network control and operation has inevitably created a number of technical impacts [2]. One of the most commonly found and most serious problems for the distribution network operators (DNOs) is voltage rise at the DG connection point [3]. For a long time, distribution networks have been designed to deliver power from transmission systems to lower voltage networks and end users. It is also obligatory practice that the DNOs provide voltage levels in the networks within a range defined by statute [4]. Depending on the size and type of DG, the impact on voltage level may vary, however, a larger capacity of DG can see voltage exceed the limit, specifically, in rural areas expected to accommodate new wind farms [5-7]. Potentially, the increased capacity and variation of DG can alter the existing voltage regulation as well as other control devices in coping with the voltage rise and voltage variation impacts [3, 8]. With the need to meet the target for renewable DG, the increased volume of power generation will also tend to stress the thermal limits of the network components [9]. Together these network constraints create a significant problem as they limit the available capacity of the network to accommodate new DG connections. To mitigate such impacts, the traditional solutions generally include, e.g., installing additional voltage regulators near DG, line re-conductoring or reinforcing specific parts of the networks [10]. An alternative concept, known as 'Active Network Management' (ANM), is also being developed and trialled to manage network constraints in a smart and more active manner, maximise the use of existing assets, release extra headroom and allow greater connection of DG [9-14].

ANM is seen as a transition step towards 'smart' distribution networks. A wide spectrum of ANM approaches range from fully 'centralised' methods requiring extensive sensing, communications, optimisation and control infrastructure through to more 'decentralised' approaches that rely on local information with minimal communication and optimisation. The centralised active management approach will likely involve high upfront costs whereas the more local control methods can lower the investment. During the development of these advanced control solutions, not only the performance feasibility but also the economic viability will be the most important factor for the DNOs. To avoid the subsequent high investment upfront (as well as of the traditional network upgrades), the decentralised control approach can be seen as a promising alternative. With voltage rise and line overload constraints the most common limitation on DG connections, in this context, this research aims to develop an adaptive control scheme to provide local management of the voltage and thermal issues in distribution networks connected with wind generation. Focusing on the decentralised management approach, the developed scheme will tackle multiple constraints that occur simultaneously and in real-time. The scheme will also be able to offer a feasible and economically viable alternative to the centralised ANM.

## 1.2 Research Hypothesis, Objectives and Scope

The hypothesis of this research is:

> Adaptive control for active distribution networks will enable distribution networks in accommodating increased capacity of DG whilst being able to manage the voltage rise and line overload occurring simultaneously. The decentralised control schemes will provide effective, corrective, and local voltage and thermal constraint management in real-time. Its extensions will allow for increased flexibility to better capture the severity of and cope with both network constraints and enable the greatest potential in energy export.

The objectives and scopes of this research include the followings:

1. To examine the behaviour and severity of voltage rise and line overload constraints due to the wind variability issue and increasing connections of wind in rural distribution networks;

2. To extend previous work on intelligent, decentralised control of DG for voltage rise mitigation to develop an active management scheme that is capable of managing the voltage rise and line overload problems in real-time;

3. To develop coordinated and centralised control approach for active network management in order to offer comparisons with decentralised control;

4. To compare the performance of the developed active management schemes on the basis of economic viability, technical feasibility, risks and benefits and wind penetration.

## 1.3 Research Methodology

In this research, the voltage rise and line overload problems in distribution networks connected with variable wind power have been considered. The decentralised voltage control scheme employing regulation of the DG unit active and reactive power is proposed. It is a significant extension of previous work [15-17] where a series of new techniques for the reactive power control and a generation curtailment of the decentralised control have been developed. The scheme also extends its control capability by taking into account the line overload constraint and is able to operate in real-time where both constraints overlap. An operational windows approach is also developed to further improve the performance based on severity of constraints and time. The decentralised control features have also been adopted in the coordinated and centralised control approaches in order to compare the control performance. Voltage regulation of the on-load tap changing (OLTC) transformer is used to enhance the voltage management in a coordinated control environment. Based on a similar aspect of previous work [18] but in a different way, an optimisation tool is implemented to provide an optimal solution to the voltage and line overload constraints. Finally, cross comparisons of the proposed schemes on the key basis of wind penetration, control performance feasibility and economic viability are carried out.

The control schemes are developed under four main criteria. Firstly, the decentralised control scheme is developed to provide a real-time and local control of the network constraints occurring at the point of wind connection. The proposed decentralised scheme is believed to provide effective management at reduced upfront costs in contrast with the traditional network reinforcement or other centralised control techniques. Here, it is assumed that the DNOs and DG developers wish to achieve the maximum possible energy exports. Therefore, the control method allows for flexibility in managing the active power output in a way that the amount of wind output will be curtailed only when necessary while respecting the voltage and line capacity limits. Secondly, it makes use of only available input data at the connection point and therefore can avoid additional investment in devices, reinforcements and communication links that would other wise be required. Thirdly, it is adopted to cope with the variability of wind generation, which mainly affects the voltage and line flow characteristics. And fourthly, provided that active management of the distribution networks with DG integration will be significant on a larger scale and in a longer term, this research also develops the active voltage and thermal overload management using the coordinated and centralised approaches based on the decentralised management. This shows that the decentralised scheme can be scalable and adaptable in order to be embedded into larger-scale distribution networks.

The validity of the proposed decentralised and coordinated voltage and thermal constraint management has been performed through:

- Simulation scenarios considering a worse case of the test networks with minimum demand and maximum generation in time series analysis;
- Historic demand and generation data during a summer period and on days with the highest wind speeds;
- Test distribution networks being rural network models to indicate the likelihood and severity of occurrence of both constraints.

## 1.4 Thesis Contributions and Deliverables

For many years and during the time of carrying out this research, almost every aspect involved in DG integration in distribution networks has been of great interest to industrial and academic researchers. The concerns are particularly the negative consequences of connecting large volumes of DG to the networks. Where voltage rise has given the DNOs a major challenge to DG connection, a number of control techniques have been developed. The majority of these techniques have concentrated on methods that are centrally integrated and executed through series of snapshot worse cases but only a few actually look at cases with higher resolution in time, e.g., time series in minutes or seconds. This is particularly the case for variable generation. Essentially, thorough control with the ‘time step by time step’ actions has to be analysed for an active management scheme to be effective in operation. Furthermore, the method that can offer technical feasibility and economic viability would be more valuable to the DNOs.

Herein, a novel scheme aims to cope with those concerns in an alternative way. Focusing on operating in a decentralised control manner, it has been developed to provide real-time management of the voltage rise problem due to increasing wind connection capacity in rural distribution networks. The reactive power control is combined with the active power curtailment based on a defined priority in order to enhance the voltage management capability where a range of the decentralised techniques are developed. The active power curtailment methods are extended to cope with the line overload constraint that exists concurrently with the voltage rise. In the operational windows approach, by utilising time-series simulations with a narrower time step, the schemes are able to define severity of constraint situations and apply the corresponding corrective control actions in real-time. The methods have been proved to provide effective control through a number of validations, simulation scenarios and case studies. With this aspect, the schemes avoid considerable costs of additional infrastructures such as communication links that may be required if the centralised control means was to be implemented.

Along the active management spectrum, a degree of coordination is also added to the developed schemes by coordinating with the voltage regulation of the OLTC in order to improve the voltage control performance. Moving along to a fully centralised approach, the optimisation technique is employed based on the same control purposes. The overall performance comparisons of the decentralised schemes and the centralised approach are carried out and can be used as a potential and useful indication for the active network management implementation.

This research is funded by the SuperGen FlexNet Consortium and is part of the research topics under the 'Smart, Flexible Controls' work-stream [19]. The outcomes also provide innovations for active network management for voltage rise and line thermal overload. Control algorithm executed files in PSS/E interfaced Python and the simulation environment are also provided to be reapplied or adapted. Through validated simulation scenarios, results demonstrating the control mechanisms and the control performance over voltage and line flows have been produced. Furthermore, assessments of the comparative novel methods on the basis of various measuring factors have been evaluated. The developed scheme(s) are believed to be alternative and useful solutions for DNOs and DG developers with the potential to become an interim step towards smart distribution networks.

## 1.5 Associated Published Work

Overall, there are six publications, including one publication from an industrial placement. The full papers are provided in the Appendix.

**Journal Publication**

1. T. Sansawatt, L. F. Ochoa, and G. P. Harrison, "Smart Decentralized Control of DG for Voltage and Thermal Constraint Management," *IEEE Transactions on Power Systems*, In press.

**Conference Papers**

2. T. Sansawatt, J. B. O'Donnell, L. F. Ochoa, and G. P. Harrison, "Decentralised Voltage Control for Active Distribution Networks," presented at *44th International Universities' Power Engineering Conference (UPEC 2009)*, Glasgow, 2009.

3. T. Sansawatt, L. F. Ochoa, and G. P. Harrison, "Decentralised voltage and thermal management to enable more distributed generation connection," presented at *CIRED Workshop*, Lyon, 2010.

4. T. Sansawatt, L. F. Ochoa, and G. P. Harrison, "Integrating distributed generation using decentralised voltage regulation," presented at *IEEE Power and Energy Society General Meeting (IEEE PES GM 2010)*, Minneapolis, USA, 2010.

5. T. Sansawatt, L. F. Ochoa, and G. P. Harrison, "Operational Windows for Decentralized Control of Renewable DG: Techno-Economic Trade-offs," presented at *IEEE Power and Energy Society Innovative Smart Grid Technologies Europe (IEEE PES ISGT Europe 2011)*, Manchester, 2011.

**Technical Report**

6. T. Sansawatt, Harmonic Assessment of Skegness Distribution Network, E.ON Engineering, 2010.

## 1.6 Thesis Structure

The thesis consists of seven chapters and four appendices as follows:

**Chapter 2** describes background knowledge associated with distributed and renewable generation and its integration in electricity distribution networks. It also explains the technical challenges faced due to the connection of renewable distributed generation. It concentrates on voltage variation and line overload constraints which lay out the main motivation of this thesis.

**Chapter 3** gives an explanation of the active distribution network spectrum and surveys existing active network management approaches to manage voltage rise and line overloads. Active management activities on voltage, power flow and multi-constraints solutions are also discussed followed by an introduction to Smart Grids in the UK, Europe and US.

**Chapter 4** presents control algorithms of decentralised control schemes to mitigate voltage variation and line overload problems in distribution networks. It details the control mechanisms of a series of methods developed for decentralised control. Validations, case studies and performance comparison of the methods are also presented.

**Chapter 5** introduces an approach called 'Operational Windows' as an enhancement of the joint decentralised management of voltage and thermal impacts to better capture and manage severity of constraints. Validation, case study and performance assessment of the approach are presented. The results are discussed and compared with the decentralised control schemes on the basis of DG penetration level, control performance and economics.

**Chapter 6** extends active management to employ more coordinated and centralised control strategies. Voltage regulation of an OLTC transformer is employed in coordination with the joint management scheme to allow enhancement of voltage mitigation. An optimal power flow tool is utilised to enable the capability of optimisation in an active management scheme. The results are presented and compared with the decentralised control schemes on the basis of DG penetration level, control performance, losses and reactive power exchanges, economics and risks and benefits.

**Chapter 7** discusses the overall outcomes obtained in Chapters 4 to 6 and draws conclusions on the research. The chapter also addresses key issues for future work.

A series of Appendices covering: network, demand and wind data; simulation environment; a summary of the outcomes of the author's industrial placement; and publications are also outlined.

# Chapter 2

# Distributed and Renewable Generation in Distribution Networks

## 2.1 Introduction

This chapter presents a detailed literature survey on distributed and renewable generation and their connection to distribution networks. The chapter begins with an introduction to distributed generation (DG) and discusses its key surrounding subjects including drivers for the expansion of DG and renewable generation connection, types of DG technologies, recent development and potential for the connection of DG and policy frameworks. The discussions are based internationally with an emphasis on the UK. Background knowledge of the UK electricity distribution networks and the integration of DG and renewable generation are also described. Despite an ongoing rise in the connection capacity of DG and renewable generation, a number of technical constraints on the networks have become critical and challenge all participants. The technical constraints of most concern are addressed and the mitigation measures to support the growing connection of DG are identified. Overviews of current practices for planning for connection and trends for future deployment and integration of DG and renewable technologies are also presented. Finally, the transition in the way that existing networks are operated towards Smart Distribution Networks is introduced.

## 2.2 Distributed Generation: A Definition

Prior to introducing a definition of DG and other related issues, it is useful to recall a brief background on what had constituted the connection of DG in the electricity distribution networks. Historically, large central electricity generators in the UK were only connected to a high voltage (i.e. 400kV or 275kV) supergrid or transmission system which then supplied the bulk capacity of power to lower voltage distribution networks across the country. The distribution networks then distributed power to the load. With the absence of local (large) generators, the operation and regulation of the distribution networks were only designed to suit a unidirectional power flow (i.e. from the transmission systems to the load). The design of this passive power flow architecture was initially for a technical and economic purpose, realising its capability to meet the demand. In the past decades, the national energy consumption in all sectors including electricity had been increased [1]. This indication had signalled a need to modify the power supply system so as to escalate the power generation capacity. In addition, the concerns for climate change and carbon emissions impacts have placed a momentum on searching for new generation from cleaner resources such as renewables. These together with the development of technology have enabled a more decentralised form of the power supply to be generated closer to demand. The change also allows new and smaller scale power generation being produced from low-carbon and renewable-based resources to be connected to the distribution networks. The decentralised power generation connected at the distribution level is termed ‘Distributed Generation’.

Despite the widespread penetration of DG technologies around the world, there has not been a specific definition given to clearly describe DG. DG may be defined as any generation of low-carbon sources including CHP that are connected directly to the distribution network where the electricity generated is used by the local community [20]. In the Polish power system, DG refers to small installations or power stations with the capacity range between 50-150 MW that are connected to distribution network or located on consumers side and produce electricity using different resources including conventional fuels, often cogeneration with heat (CHP), and renewables [21]. As presented by Guan *et al*, DG in the Chinese power system may be defined as being small generating units that combine the use of energy storage and power generation systems produced by the environmental-friendly resources and are installed on the users side [22]. According to the Energy Network Association (ENA) [23], in the UK, DG is described as a generating unit which is connected at distribution level where the maximum voltages are 132kV in England and Wales and 33kV in Scotland and the generation capacity is generally less than plants connected to the transmission system.

Ackermann *et al* have examined various definitions of DG and its characteristics that are used in different countries such as Sweden, England, Wales, Australia and New Zealand. The criterion to distinguish amongst those definitions is mainly the output capacity of DG as a result of different governance and accordingly the electricity regulations [24]. In order to avoid confusion from the various meanings seen by different countries, Ackermann *et al* suggest a general definition of DG [24]:

> "Distributed generation is an electric power source connected directly to the distribution network or on the customer side of the meter"

Where climate change is of concern, a common character of DG may also be represented by being low carbon-sourced and energy-efficient generation that is connected to a distribution network.

Whereas the term DG is widely used in many countries, there are also other terms with a synonymous meaning. For instance, embedded generation is used to describe the generation that is embedded directly to distribution networks to supply electricity closer to loads [25]. In view of the National Electricity Transmission System (NETS, National Grid), embedded generation can also be defined as medium and small power stations that contribute their output to the grid supply points and are categorised into two groups: (i) the generation for own use, normally in the form of CHP, and (ii) the generation to supply third parties, mainly from renewable resources [26]. Although those power stations are connected at distribution level and are not directly seen by the transmission system, the overall output and operation can have an impact. Dispersed generation is also a synonymous term used to refer to the generation that is not centrally planned nor dispatched, is connected to distribution networks and has a capacity of smaller than 50 – 100 MW [27].

There are diverse definitions and expressions to describe this type of generation however those terms are interchangeable. A consensus to define what category such generation is to be termed relies on a range of factors which can be summarised as [24, 27, 28]:

- Purpose of distributed generation;
- Voltage level to which the generation is connected;
- Location of the generation;
- Type of technologies;
- Maximum power rating of the generator;
- Role of the generator for dispatching;
- Ownership;
- Government's electricity market regulations.

From the above factors, one basis that may be useful to all power system users when describing DG is to specify the maximum rating of the generation. Ackermann *et al* introduce four categories of DG based upon the maximum capacity as follows:

- Micro DG ~1 Watt < 5 kW;
- Small DG 5 kW < 5 MW;
- Medium DG 5 MW < 50 MW;
- Large DG 50 MW < 300 MW.

In this thesis, the term DG with a maximum capacity between small to medium scale, being capable of producing active and reactive power and connected to a distribution network at 33kV or 11kV is considered throughout.

### 2.2.1 Drivers

There are a number of reasons that have contributed to expansion of DG penetration in electricity distribution networks. This section summarises and discusses the following contributing factors [23]:

- Environmental concerns and climate change;
- Continuing increase in energy demand;
- Technological innovation;
- Liberalisation of electricity markets;
- New Government policy.

**Environmental concerns and climate change**

A concern over climate change is one of the major motivations for growth of DG. As described by the United Nations Framework Convention on Climate Change (UNFCCC), the continued emissions of greenhouse gases, especially $CO_2$, over the past decades have caused numerous changes in global climate [29]. These changes will lead to serious consequences in natural systems on all continents and most oceans, for instance, impacts on fresh water resources, ecosystems, food, forest products, coastal areas, human health and industry and society which use climate sensitive resources [29]. In response, the Kyoto Protocol, an international agreement linked to the UNFCCC, was established in order to reduce global emissions of greenhouse gases. The protocol sets a binding target for which 37 industrialised countries members and the European community have committed to reduce emissions. Additional details of the Kyoto mechanisms on how each member state acts to achieve targets can be found in [30].

In addition to achieving the emissions reduction, there are targets set amongst member states to increase DG and renewable energy generation. For instance, the mandatory targets in Europe are to achieve 20% share of renewables in its energy mix, together with 20% reduction in greenhouse gases emissions and 20% more energy efficiency [31, 32]. In the UK, the legally-binding target is to ensure, by 2020, 15% of its energy generation is produced from renewable resources. As suggested in the UK Renewable Energy Strategy report [33], this target could be met by using a "lead scenario" which comprises 30% of electricity, 12% of heat and 10% of transport energy produced from renewables.

## Continuing increase in energy demand

It is important that the supply margin for heat and electricity is readily available to meet the demand growth. From 1990 to 2007, world energy demand increased by approximately 1.3 percent per year, with the net demand expected to grow until 2035 (Figure 2 - 1) [34]. This implies a need to plan additional electricity generation and in many countries, the additional generation will be obtained by increasing the penetration of DG.

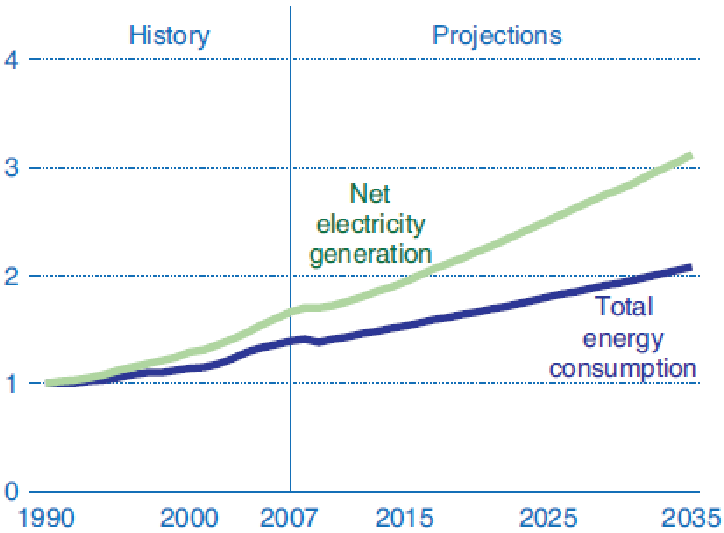



**Figure 2 - 1: Growth in world electric power generation and total energy consumption between 1990-2035 (index, 1990 = 1) [34]**

In the UK, there is also a trend of continuing increase in electricity demand, as shown in Figure 2 - 2. Between 1980 and 2008, it is observed that electricity consumption in services, domestic and industrial sectors grew almost every year [1]. Despite the uncertain situations that can affect electricity demand, the trend of continuing increase in demand suggests a need to ensure that sufficient electricity supply can be achieved.

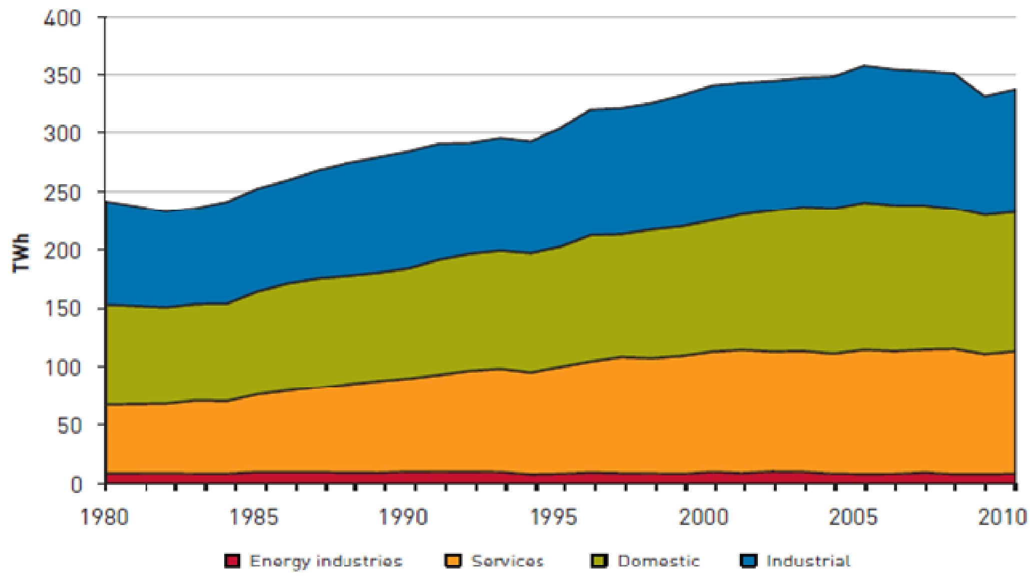



**Figure 2 - 2: Electricity consumption in UK between 1980 – 2010 [1]**

It is expected that a significant proportion of the generation would be produced from DG. In the UK, large-scale DG technologies, e.g. onshore and offshore wind, hydro generation and CHP are potential sources that will contribute to the capacity margin so as to provide a generation mix to improve system reliability, affordability and efficiency. Smaller scale generation such as solar photovoltaic and micro-generation will also play an important role in meeting the demand growth.

**Technological innovation**

Technological innovation has enabled more energy generation from renewable resources. In many countries, recent research and development of DG technologies have been focused on utilisation of existing renewable resources for electricity and heat generation. Technological innovation also enables maximisation of power generation. Wind turbine technology now covers a capability to generate electricity in a range of small kW up to 10MW [35]. In the UK, wave and tidal technologies are still at the research stage however there are a number of designs to improve energy capture and minimise environmental impacts.

Furthermore, new technology development allows the connection of DG to be more secure. Technical impacts, e.g. voltage rise, overload of lines or fault levels that arise from increased DG connection can be better mitigated by means of Active Network Management (ANM). Moreover, there are currently a number of control and management tools being developed to overcome these challenges. Details of ANM, its recent development and related issues will be presented in Chapter 3.

**Liberalisation of electricity markets**

The reform of the monopolistic structure of energy markets, particularly in the European Union, has an intention to deliver security, reliability and efficiency of the electricity supply at competitive prices. In England and Wales, deregulation of the electricity industries appeared in 1990 which brought several advantages compared to before privatisation, for instance, increase in labour productivity, reduction in fuel costs and new generation plants at considerably lower unit cost [36]. In particular, liberalisation and privatisation of the electricity market have encouraged new investment in generation technologies that are more localised and have better financial viability.

**Government policy**

Government policy concerning national energy generation provides a vital support for development and expansion of DG. Having awareness of climate change, many countries have reviewed and implemented policies to concentrate on reducing greenhouse gas emissions and increase renewable generation. In the UK, the Department of Energy and Climate Change (DECC) has brought together energy policy and climate change mitigation policy in order to lead in tackling the climate change challenges. There are four key policy areas under consideration [37]:

- Global climate change and energy
- UK energy supply
- Supporting consumers
- A low-carbon UK

These policy areas are developed to ensure that energy supplies for the UK are secure, reliable and produced from a mix of generation sources that are affordable, low-carbon and price competitive. The policies also aim to improve energy efficiency and encourage the introduction of low-carbon technologies that can be achieved by means of expanding the integration of DG into distribution networks.

### 2.2.2 Distributed and Renewable Generation Technologies

Advances in research and technology have enabled DG development to utilise a more variety of resources. In particular, low-carbon and renewable-based sources have great potential in contributing to carbon emission reduction targets. Existing DG technologies also cover a range of scales. This section explains the low-carbon and renewable DG technologies that are being exploited and connected to distribution networks.

**Wind**

Wind energy is the fastest growing technology in terms of percentage of annual installed capacity per technology source [38]. Wind resources both onshore and offshore have been the most potential source for electricity generation in many countries. In the UK, wind resources particularly offshore offer a major opportunity due to the strength and consistency of the winds sweeping across the country and the surrounding waters [39]. The UK's offshore wind sector became the first to achieve the overall installed capacity of 1GW. For onshore wind, currently the installed capacity is approximately 4.5GW [40]. Potentially, onshore and offshore wind will provide a significant contribution to meeting the UK's ambitious target for renewable electricity generation.

Theoretically, power is a function of wind speed ($V$, m/s) and the area ($A$, $m^2$) that the wind flows through. The power extracted from a wind turbine is given by [38]:

$$P = \frac{1}{2}\rho C_P AV^3 \qquad (2 - 1)$$

where $\rho$ is air density ($kg/m^3$) and $C_P$ is a power coefficient which varies with the speed of the wind.

In extracting power, several wind speeds are important: (i) cut-in wind speed; (ii) rated wind speed and (iii) cut-out wind speed [38]. As depicted in Figure 2 - 3, the cut-in wind speed is typically between 3 m/s to 4 m/s. Once a wind turbine has started, it will continue to generate power and will usually reach its rated capacity at 12 m/s, depending on the wind turbine design. Typically, a wind turbine can operate up to around a speed of 25 m/s when it will cut-out to prevent failure. Wind speed varies with altitude, air temperature and topography. Good wind sites are for instance at the tops of smooth hills, open areas or shorelines with low concentration of obstacles. Despite being the fastest growing technology for electricity generation, power produced from wind is considered to be the most variable.

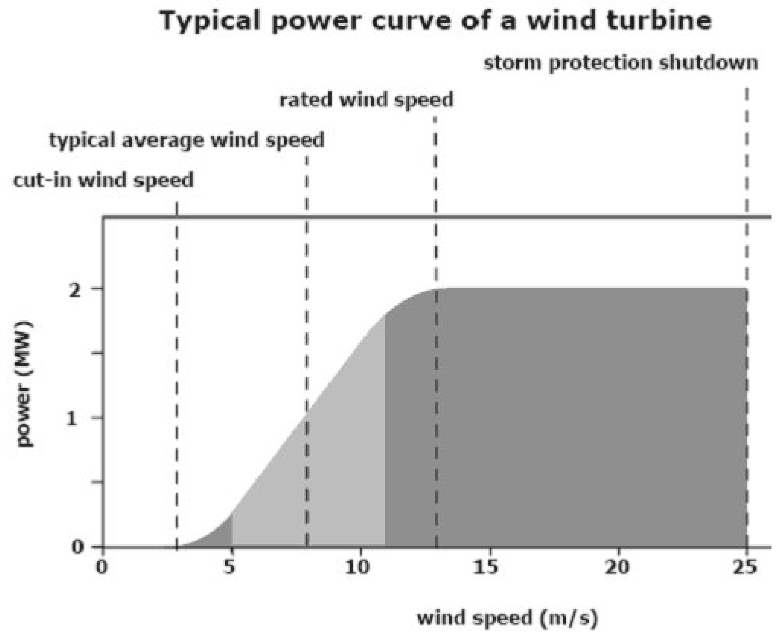



**Figure 2 - 3: Typical power curve of a wind turbine [41]**

## Wave and Tidal

Waves are created by the flows of wind passing over open bodies of water. Some of the energy is transferred to form waves [42]. The amount of energy in waves depends on the wind speed, the length of time that the wind blows and the distance the wind blows across the water.

Another form of marine energy source for electricity generation is tidal, derived by the combined gravitational forces of the Moon and the Sun that creates the movements of the ocean. Because of its dependency upon the interaction between the moon and the sun, tides are predictable. This significant advantage of tidal source makes it one of the most potential resources for clean electricity generation.

Tidal power can be produced by two methods [43]: tidal barrages and marine currents. Tidal barrages tend to be large scale installations but marine currents can be exploited at a range of scales. Rapid marine currents are formed primarily by tides in narrow channels [43]. The flow of marine currents drives turbines using the same principle as for wind turbines.

The major difference of marine currents compared to wind energy extraction is the power density and the operating velocity of the stream or wind to which the energy can be fully produced. The power density of marine currents develops at much lower stream speeds, i.e., around 2 to 3 m/s [43]. Wave and tidal technology is currently still being developed in many countries including the UK.

## Solar

Solar energy is obtained through a direct conversion of energy stored in sunlight into useful forms, mainly heat and electricity. The solar energy technologies currently being developed comprise four branches [44]: Photovoltaic (PV), Solar Thermal Electric, Passive Solar Design (PSD) and Active Solar.

Out of these technologies, Photovoltaic and Solar Thermal Electric are the two branches developed for electricity production. Photovoltaic produces electricity by capturing solar radiation and directly converting it into electricity using semiconductor or photoelectric materials such as silicon. These materials can be arranged into two or more layers to form a solar PV cell.

Worldwide, solar PV systems in used range from very small-scale domestic application (small kW) to large central plant (up to 80 MW), providing a global installed capacity of over 2500 MW [44].

**<u>Hydropower</u>**

Hydropower is based on a conversion of the potential energy of water stored at higher levels [45]. There are several methods for hydropower generation such as conventional (storage or dam), run-of-river and pumped-storage. Water or hydro has been used to generate electricity for hundreds of years and is the most significant renewable resource that has been exploited to date [46]. Worldwide, hydroelectricity of medium to large scale plants provides the largest share of total renewable generation and is the predominant source amongst other renewable energy types [34]. During 2009 period, large-scale hydropower plants accounted for the third largest share of renewable energy sources used in the UK, after biomass and wind generation. Significant smaller hydro potential remains.

**<u>Bioenergy</u>**

Bioenergy is the energy produced from biofuels which are derived from biomass or bio waste. Organic matter that is obtained directly from plants such as energy crops and coppices, or indirectly from domestic, industrial, commercial wastes and agricultural by-products are classified as biomass. There are various types of biofuels derived from these organic matters, i.e. vegetable oil, biodiesel, bioalcohol, ethanol fuel and biogas. The generation system of bioenergy varies from combustion in stoves and boilers to pyrolysis, gasification, anaerobic digestion and fermentation.

In the UK, the use of biofuels for energy production including heat and electricity in 2010 contributed to the largest share (80.7%) amongst other renewable resources [1], as shown in Figure 2 - 4. Biofuels have received great attention worldwide as being a potential alternative form of fuel to fossil fuels, however, the environmental and economic viability may not yet be verified.

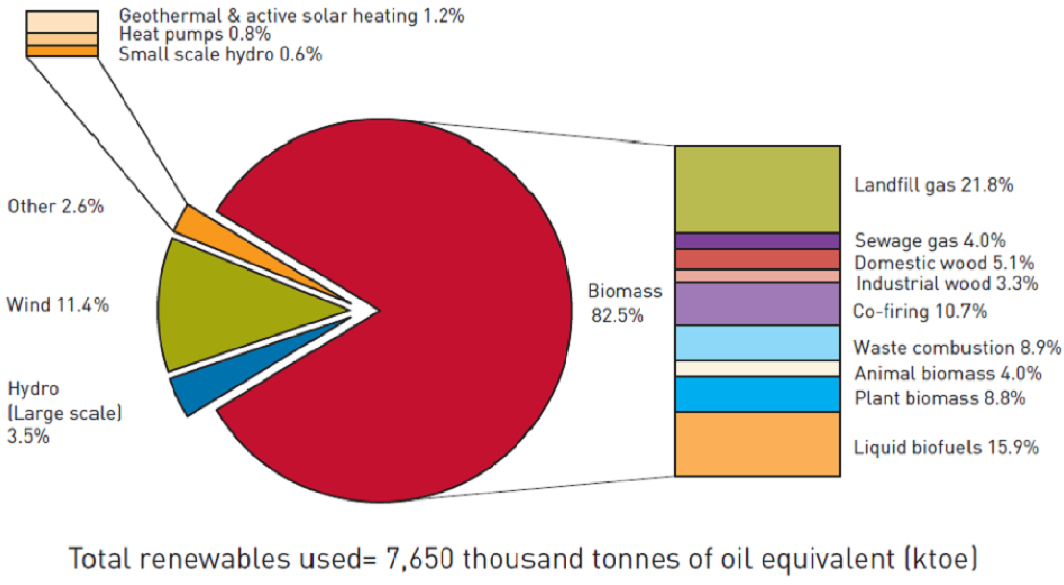



**Figure 2 - 4: Share of UK renewable energy sources in 2010 [1]**

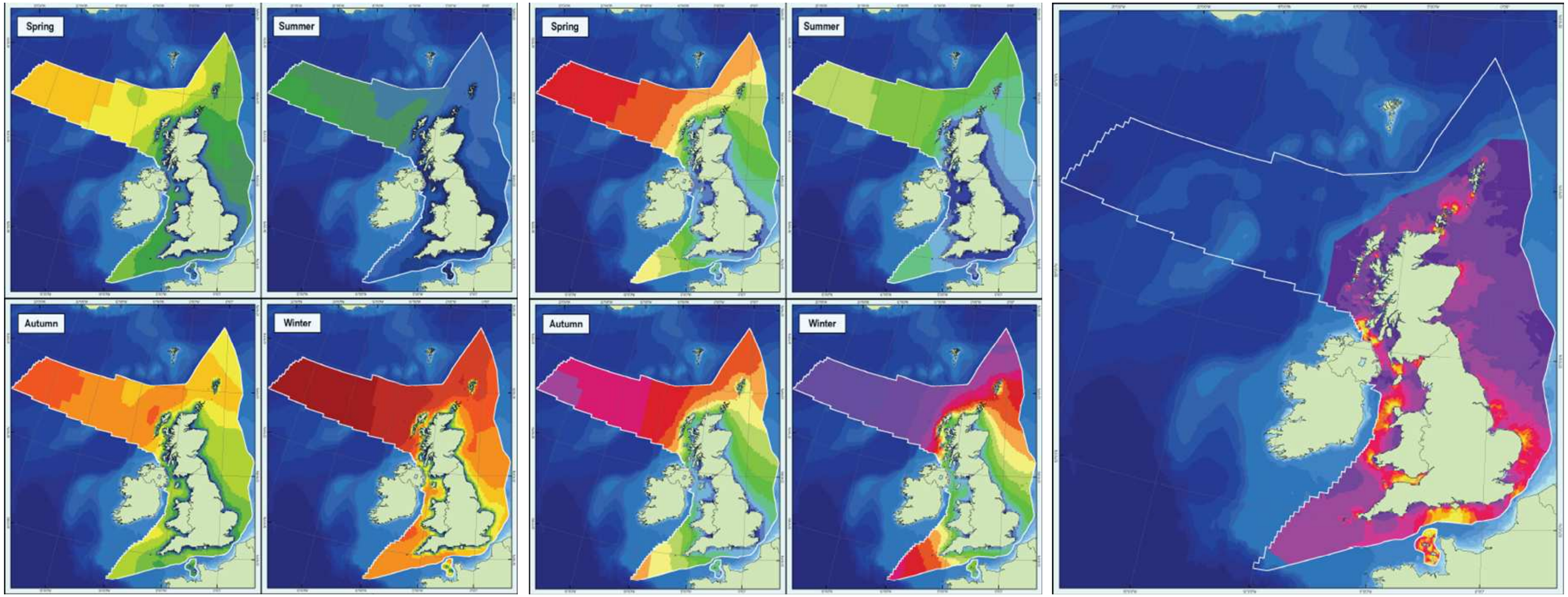
**<u>Microgeneration</u>**

Microgeneration covers a wide range of electricity and heat generation technologies at small-scale and measured in kW. The definition of microgeneration has not been clearly described however it appears to be most commonly used in the context of the generation at domestic scale that is connected in parallel with public low-voltage networks. The technologies cover generation up to 50 kW for electricity and 45 kW for heat [20]. Microgeneration can also refer to small-scale embedded generation as defined in the Engineering Recommendation G83/1 [47]. Examples of microgeneration technologies include small scale wind, small scale hydro, solar thermal, ground source and air source heat pumps, biomass and solar PV.

### 2.2.3 Recent Development and Potential in the UK

Distributed and renewable generation development in the UK primarily offshore and onshore wind and marine energy has been growing fast. The availability of renewable resources is dependent on geographical location and topology. As depicted in Figure 2 - 5 (a), offshore wind speeds are higher and more extreme in the north than the other areas of the country and in Scotland. Wave resources are affected by wind speeds and therefore wave heights are high in the northern region

(Figure 2 - 5 (b)). Tidal resources develop high speed current flows usually in narrowing channels such as straits between islands in the West, the South and around Orkney islands (Figure 2 - 5 (c)). This locational advantage together with the technological innovation has supported the UK in developing leading-edge technologies for wind, wave and tidal energy.




**(a)** **(b)** **(c)**

**Figure 2 - 5: Seasonal mean wind speed (a), seasonal mean significant wave height (b) and mean spring tide peak flow (c) [48]**

Seasonality also has an influence on wind and marine resources. Wind resources in the UK has strong seasonal variations of wind speed on a daily to annual basis as can be seen from Figure 2 - 6. The study carried out by Sinden [49] presents the wind generation patterns based on a monthly scale analysed from the wind data records at a range of sites across the UK. This is a typical electricity production pattern from wind resource in the UK that can be achieved throughout a year. On average, the electricity production from wind is around twice as much during the winter months (December, January and February) compared to the summer months of June, July and August.

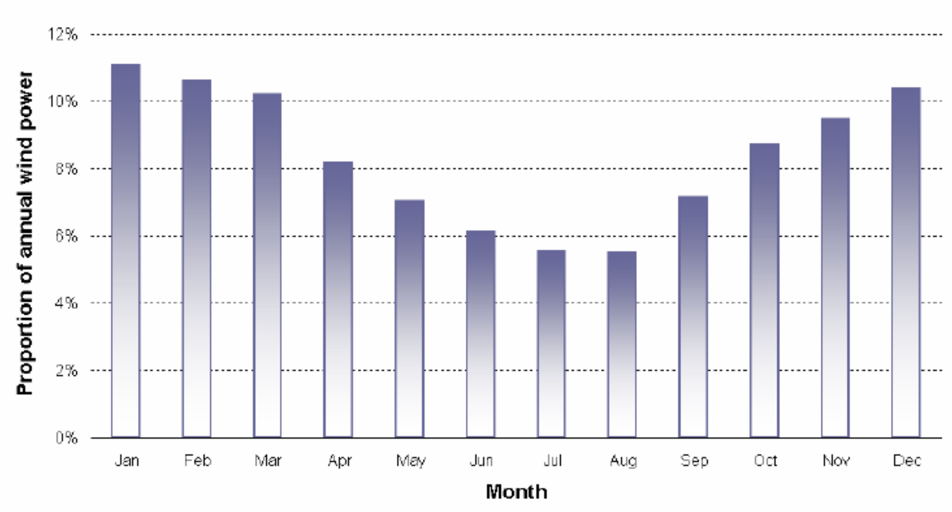



**Figure 2 - 6: Variation in average monthly wind power output [49]**

### 2.2.4 Incentives and Policy Frameworks

The role of renewable and distributed generation has become increasingly important to help meeting the targets for greenhouse gas emissions reduction and increasing the share of renewable electricity generation. In assisting this potential role, a number of government support mechanisms have been implemented to motivate the deployment of renewable energy technologies. Most of the mechanisms come in the form of a market-based approach which also encourages the energy market for renewables in addition to conventional resources.

The support mechanisms can be categorised into two types: direct support for renewables comprising the Renewables Obligation (RO) and the Feed-in Tariff (FIT) and indirect support mechanisms via distribution network operators, comprising Innovation Funding Incentive (IFI) and the Registered Power Zone (RPZ) which support connection of DG.

In the UK the Renewables Obligation is an obligation for electricity suppliers to source a specific and growing proportion of electricity produced from renewables [37] and is designed to incentivise renewable-based generation to enter the electricity market [50]. Accredited electricity suppliers will be issued with a Renewables Obligation Certificate (ROC) for each unit of electricity (in MWh) produced and supplied to customers. Most renewables are eligible.

The Feed-in Tariff is a payment to electricity consumers who install eligible generators for every unit (kWh) of electricity produced, even though it is self-used [51]. Consumers also receive additional bonus payments for electricity that is exported to the grid. The FIT came into practice in April 2010 with a goal to incentivise small scale and low carbon electricity generation. Eligible generating units that are entitled to the FIT cover most of renewable electricity technologies which with capacity up to 5 MW.

The Innovation Funding Incentive is a mechanism to provide funding for R&D projects in distribution and transmission networks to deliver improvement and benefits in terms of financial, security and quality of supply and environment to consumers [52]. The projects entitled to the IFI can comprise any aspect of the network asset management that ranges from design to construction, commissioning, operation, maintenance and decommissioning [53]. Many projects relate to DG. Some examples of successful IFI projects include the Dynamic Ratings Project (E.ON Central Networks) to enable increased wind generation dispatched; Understanding Networks with High Penetrations of DG (E.ON Central Networks) to identify changes to network design; and Distribution Dynamic Line Rating for the Orkney distribution network (Scottish and Southern Energy Power Distribution) to estimate a real time rating for overhead lines using real time weather and conductor temperature measurements.

The Registered Power Zone is a financial support scheme to encourage distribution network operators to develop and demonstrate new and cost effective solutions with a specific focus on the connection and operation of DG. There are currently a number of RPZ projects. The Active Network Management (ANM) scheme in Orkney Isles, carried out by Scottish Hydro Electric Power Distribution is one example. The scheme provides advances in system planning and operation of electricity generation from wind and marine connected to the Orkney distribution network in order to maximise the generation capacity. Detail on the operation of the Orkney ANM scheme is provided in Chapter 3.

## 2.3 The UK Electricity Distribution Networks

This section describes the UK electricity distribution networks where renewable and DG technologies are primarily connected. Background knowledge on types of distribution networks and voltage regulation are discussed.

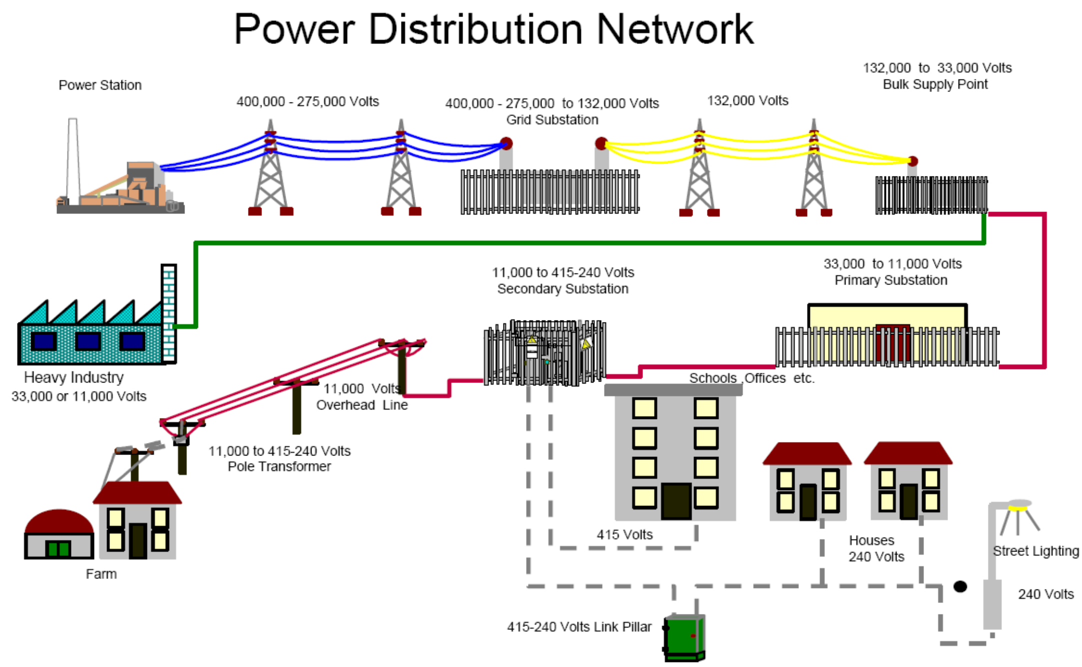



**Figure 2 - 7: Structure of electricity network in the UK [54]**

The UK electricity network structure is illustrated in Figure 2 - 7. The network comprises four main components: (i) generation, (ii) transmission, (iii) distribution and (iv) demand. Each component is interrelated by different voltage levels that range from extra high voltage (EHV, above 300 kV) to low voltage (below 1 kV) [55]. Large central electricity generators are connected to transmission systems at 400 kV and 275 kV in England and Wales and 132 kV in Scotland. The transmission system then carries the bulk capacity of power to supply lower voltage distribution networks across the country. At grid supply points, the power is transferred onto the distribution network at which the voltage level is reduced to 66 kV, 33kV and 11 kV (MV system). At the end of the network, the power voltage is stepped down to LV at 400 V and 230 V for consumers. This network structure and its operation predate the emergence of distributed and renewable generation connections. The integration of DG and its surrounding issues are discussed in Sections 2.4 and 2.5.

The distribution networks are owned and operated by Distribution Network Operators (DNOs). There are fourteen licensed DNOs in England, Wales, Scotland and Northern Ireland currently. The DNO is responsible for the operation and maintenance of a public electricity distribution network [56]. One DNO may own more than one area, however, in each area there is only one owner or operator responsible for providing secure and reliable electricity supply to its customers. The DNOs are monopolies and are regulated by Ofgem. Ofgem uses a price control regime in order to ensure efficient electricity supply from each distributor, maintain a fair return to the distributors after capital and operating costs and limit the amounts of electricity charges to consumers [57]. The DNOs also undertake distributed generator connections. In summary, the main responsibilities of the DNOs for their registered areas are: to protect the network from faults; to maintain voltage levels within statutory limits; to ensure thermal ratings of equipment and fault ratings of switchgear and cables are not exceeded; to minimise voltage disturbance; to ensure quality of supply and maintain networks; and to arrange DG connections. Despite the connections of DG within the operating areas, the DNOs pay attention to demand customers as the first priority and that the network security and reliability are maintained.

### 2.3.1 Types of Network Configurations

Distribution network design can be categorised into various arrangements. In general, there are five main configurations that are typically used: (i) mesh; (ii) interconnected network; (iii) link arrangement; (iv) open loop and (v) radial system, as illustrated in Figure 2 - 8 where individual substations are represented by circles. Each type is beneficial in different aspects. The mesh and interconnected arrangements can provide security of supply to individual substations and are frequently used in HV transmission systems. The link arrangement is similar to the interconnected network that links between two infeed substations. This system can operate as two radial substations by opening the interconnectors while having an option for closure of the open points in order to restore supplies if one of the infeed substations is out of service. The open loop arrangement also provides security of supply in that, when a fault occurs, the faulted section can be isolated while the normally open points are closed to provide back-up supplies. The radial configuration is commonly used in LV rural networks where the systems are less complex and the fault occurrence is infrequent.

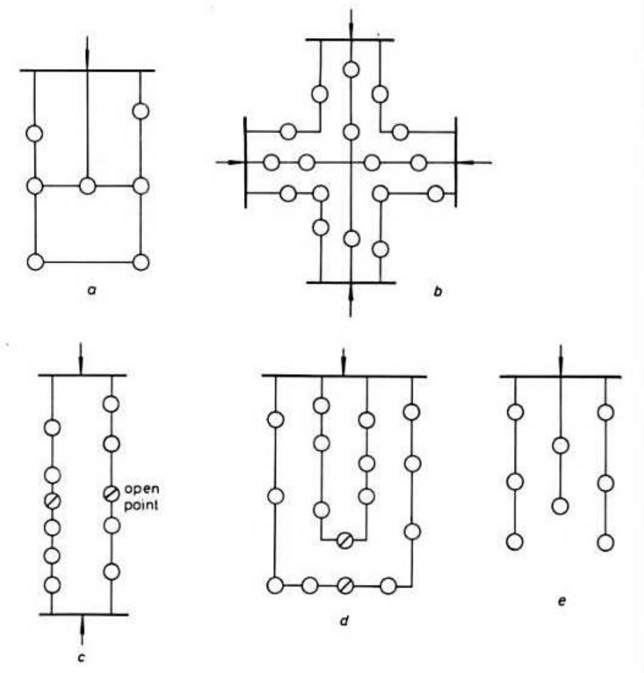



**Figure 2 - 8: Network configurations: (a) Mesh network, (b) Interconnected network, (c) Link arrangement, (d) Open loop and (e) Radial [55]**

### 2.3.2 Conventional Voltage Regulation

The voltage level at each connection point in distribution network must be regulated to satisfy the upper and lower limitations defined by statue. The Electricity Safety, Quality and Continuity Regulations 2002 specify the permitted variations for the steady-state voltage of the UK electricity systems at 50 Hz [4]:

- For low voltage supply, i.e., below 1000 V, a variation not exceeding 10% above or 6% below the declared voltage at the declared frequency;

- For high voltage supply operating at a voltage below 132 kV, a variation not exceeding 6% above or below the declared voltage at the declared frequency;

- For high voltage supply operating at a voltage of 132 kV or above, a variation not exceeding 10% above or below the declared voltage at the declared frequency.

The HV, MV and LV electricity systems are represented in a single-line feeder diagram in Figure 2 - 9. The voltage level along the feeder will tend to drop with distance from the substation where the voltage is boosted and load connected on the lower voltage side. Therefore, the voltage must be regulated within the permitted voltage variations.

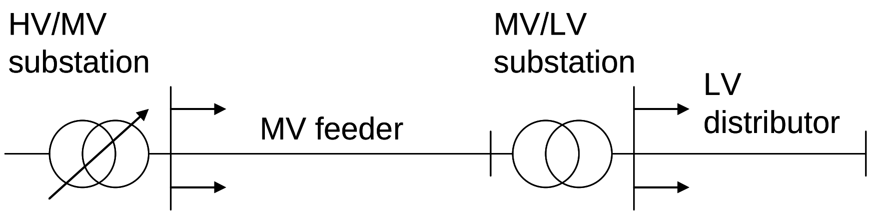



**Figure 2 - 9: Simplified distribution network structure [55]**

Voltage regulation in a distribution network can be classified into two methods: (i) direct voltage regulation and (ii) indirect voltage regulation using reactive power compensation. Direct voltage regulation is performed by a substation or distribution transformer using an on-load tap changer (OLTC) and is commonly used in HV and

MV systems, i.e., 132/33 kV and 33/11 kV transformers. The OLTC transformer, equipped with several taps, performs the voltage regulation by adjusting the tap position according to the difference between the reference voltage and the measured voltage to regulate the voltage on its secondary side that changes due to load variations. The OLTC can be actuated automatically, remotely or manually depending on the feeder characteristics and the voltage system it regulates. Automatic voltage control for the OLTC transformer is a typical practice used at the HV/MV substations where the transformer alters its winding ratio (or tapping) following an automatic relay sensing the secondary busbar voltage. Typically, the tap step for HV/MV transformers is 1.67% with a tolerance of the automatic sensing relay below twice the transformer tap step, e.g., a tolerance of 2% can be used [55]. This is for the purpose of minimising a ‘hunting effect’ caused by a continuous sequence of tapping up and down due to inappropriate tolerance level of the automatic sensing relay to initiate a tapping action. A time-delay relay is also commonly used to prevent tap change initiation during short-time voltage variations. Voltage regulation by manual tap changer is usually used at MV/LV substations, i.e., 11/0.433 kV transformer, but is only used to ensure voltage profile along the LV feeder remains within the statutory limits. Another method to provide direct voltage regulation is line-drop compensation. The line-drop compensation is applied to the voltage regulating relay of the transformer to control the busbar voltage so that it is varied depending on the connected load and to correct the voltage rise or drop.

Indirect voltage regulation adopting reactive power compensation is typically used at critical points in the network that experience voltage variations along the feeder to satisfy the permitted voltage levels. The solution can be achieved by installing shunt capacitors that provide reactive power by switching in and out using relays sensing the voltage level to overcome the voltage variations caused by load.

## 2.4 Integration of Distributed and Renewable Generation

This section provides an overview of the issues associated with the integration of renewable DG plants in distribution networks. Technical requirement guidelines, the connection configuration and the connection processes are presented.

Distributed generators desiring to connect either in transmission or distribution networks are required to comply with technical requirements as classified by the connected voltage levels and the generation capacity. In distribution networks, the generators are obliged to meet the connection requirements as outlined in the Distribution Code [58]. According to Annex 1 of the Distribution Code, the following Engineering Recommendations are referred to and specify the requirements for DG of different voltage and generation capacity [59]:

- ER G83/1 – applies to generators of up to 16A/phase, connected to low voltage systems.
- ER G59/1 – applies to generators of up to 5 MW output connected below 20kV.
- ER G75/1 – applies to generators of greater than 5 MW output or connected at a voltage above 20kV.

Prior to the connection of DG to the distribution networks, various physical and contractual arrangements must be prepared. The physical arrangements refer to electrical infrastructure, i.e., lines, cables, switchgear, transformer, civil works etc., that are required for the installation and connection. The contractual arrangements are agreements between DG developers and DNOs or third parties which cover specific issues, e.g., connection arrangements, adoption agreements and power purchase agreements. The connection of renewable and DG units comprises a number of stages in which the detailed processes vary with size of the DG plant. Generally, there are five key stages for DG connection to be undertaken [56]: Project

Planning Phase; Information; Design Phase; Construction Phase; and Testing & Commissioning Phase.

Significant volumes of new DG schemes are expected to be connected in distribution networks. Accordingly, there is a risk of conflicts between such new generation and the existing network operation and regulations. Such technical conflicts due to the presence of DG are discussed in the next section.

## 2.5 Technical Constraints of Renewable DG Connection

The connections of renewable and distributed generation to distribution networks have increased complexity in the existing network operation and regulation. Such difficulty is mainly due to a transformation of the network from passive to become more active where new generation is being connected. As a consequence, there have been a number of technical and non-technical impacts being experienced in the distribution networks. The technical-related issues arisen from the connection of DG are described in the following sections [3, 56, 60, 61]:

### 2.5.1 Voltage Rise

Voltage rise at the DG connection point is the most significant impact for the network operators and is regarded as one of the main issues in this research. As presented in Subsection 2.3.2, voltage levels beyond the transformers must be maintained within the certain limits defined by statute. The connection of new generators can cause alteration of voltage level at the connection point above these limits, particularly variable generation like wind power in rural networks. Theoretically, the voltage variation (rise or drop) between two buses of the simple two-bus feeder shown in Figure 2 - 10 can be approximated by Equation 2 - 2:

$$\begin{aligned}\Delta V = V_1 - V_2 &\approx \frac{R_{12}P + X_{12}Q}{V_1} \\ &\approx \frac{R_{12}(P_L - P_{DG}) + X_{12}(Q_L \pm Q_{DG} \pm Q_C)}{V_1}\end{aligned} \qquad (2 - 2)$$

where *R* and *X* are line resistance and reactance, respectively, and *P* and *Q* are net active and reactive power flow between the two buses. At the points moving away from the substation, lines or cables tend to have smaller cross-sectional area. This indicates that the line resistance becomes larger (lines are highly resistive); therefore, the ratio between the line reactance and resistance (*X/R* ratio) is smaller. As a consequence, active power flow has more influence on voltage change than reactive power, i.e., the first term associated with active power and line resistance. Therefore, the increased power exports from DG can potentially cause voltage rise at the point of connection.

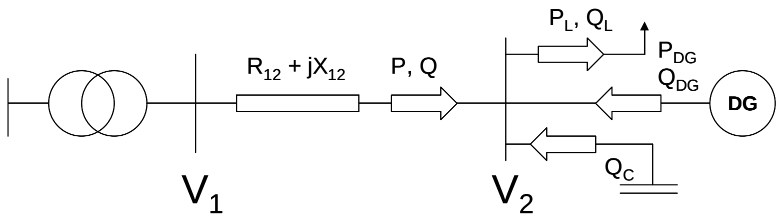



**Figure 2 - 10: Two-bus feeder [62]**

### 2.5.2 Thermal Overload

Distribution network infrastructure comprises many components, e.g., lines, cables, transformers, etc., that have a limited current-carrying capacity or thermal rating. If being loaded above this limit for an extended period, these elements will overheat and can lead to increasing losses and permanent damage of devices. The thermal rating of a device depends on a number of factors which include: load pattern, load duration, load peak, device location, surrounding temperature of the device and seasonal effects. Distributed generators connected to a distribution network have the effect of altering the current flows and changing the load shape seen by each element in the system. Although the occurrence is not frequent, the new generation level may pose the risk of current flows exceeding the thermal ratings of existing lines or cables. Thermal overload impact is also considered in this research.

### 2.5.3 Voltage Step Change

Step voltage change is typically caused by system switching, starting of a generator, fault or planned outage of the network. In this context, the connection and disconnection of DG can also cause a step change in voltage profile in the network it is connected to. The magnitude of voltage step depends on active and reactive power produced from DG, load profiles and existing voltage regulation. According to the Engineering Recommendation G75/1, the voltage step change limitation is defined at ±3% for any infrequent events and ±6% for any unplanned outages.

### 2.5.4 Reverse Power Flow

Distribution networks were historically designed to distribute power in one direction, i.e., from HV transmission systems to lower voltage networks. The connections of DG to distribution networks can result in a reverse of power flows. This occurs when the generation produced is more than local load in the system. A surplus of power is therefore exported to a higher voltage system to supply the demand elsewhere in the grid. Most distribution transformers have a reverse power flow capability that is mainly limited by two factors: rating of the transformers and tap-changing mechanism. The tap changer in some transformers is designed such that the reverse power is not possible or is limited to significantly less than the actual rating of the transformer. The tapping mechanism in some rural distribution networks have been set to provide maximum step-up to the lower voltage therefore under reverse power conditions the tapping may be inadequate to hold the low voltage within the limit.

### 2.5.5 Fault Level and Protection

Fault level is a short circuit current at the point under fault conditions, usually caused by unexpected events such as lighting strikes. Each electrical element in the network has a fault rating which refers to an ability to withstand the peak fault current. The occurrence of a fault in the network can lead to failure of generation units and other elements if immediate mitigation action is not applied. A protection system has to be installed to maintain system reliability and security as a result of fault event. Typical protection equipment used includes protection relays (i.e., switchgear), protection intertripping and auto-reclosure. Switchgear or a circuit breaker is installed to disconnect a line, a feeder or a DG unit that is connected near the fault location when the fault current is higher than the trigger level.

The rating of circuit breakers defines an upper limit on the range of fault levels that can be allowed at a particular point in the network. Typical design fault levels for UK distribution system voltages are shown in Table 2 - 1. These design levels are common standards for circuit breakers and are used by many DNOs. The connection of DG can result in increases in fault levels that may exceed the design levels in distribution networks. As specified in the Grid Code and the Distribution Code it is a requirement that DG units remain connected and withstand fault occurring within several milliseconds without tripping [58, 63]. For wind turbines, doubly fed induction generators (DFIGs) are capable of providing fault ride through in compliance with this requirement [64].

**Table 2 - 1: Typical design fault levels for UK distribution voltages [56]**

| Distribution system voltage (kV) | 11 | 33 | 132 |
|---|---|---|---|
| Design fault level (MVA) | 250 | 750 | 3500 |

### 2.5.6 Network Stability

Network stability is a state of the overall response of a power system to disturbances which are caused by loss of generation, network switching, faults or significant load changes. Two types of stability include steady state and transient stability. A DG unit installed in the network is ‘steady state stable’ if following a small disturbance, e.g., load or circuit switching, it returns to a steady state operation. The unit is considered being ‘transiently stable’ after a large system disturbance if it remains in synchronism and returns to a new steady state operating position. Both steady state and transient stability assessments may be required for the connection of a synchronous generator. In addition, for asynchronous generator, voltage stability analyses will need to be undertaken due to acceleration of the rotor (and the subsequent increase in reactive power demand) of the machine during voltage depression. Full discussion regarding the stability issue is presented in Section 9 of Engineering Recommendation G75/1.

### 2.5.7 Power Quality

Power quality issues in a distribution network mainly comprise voltage flicker and harmonics. Voltage flicker refers to rapid fluctuations in the voltage level which can affect local electricity users such as flickering of light bulbs. The connection of variable DG can be a potential cause of voltage flicker. This is peculiar to fixed-speed wind turbines connected to a weak rural network, whereas variable-speed wind turbines have less impact on voltage flicker.

Harmonics arise from the presence of harmonic components from non-linear devices such as power supplies, compact fluorescent lights, variable speed motor drives, inverter-coupled generators and power factor correction capacitors that can absorb or inject current into the system. These current-led harmonic components will cause distortion of voltage waveform of the supply from an ideal sinusoidal shape at 50 Hz at higher frequencies. The major adverse effects of harmonic distortion include heating of induction motors, transformers and capacitors and overloading of neutrals [65]. There are harmonic level standards to which the harmonic distortion at any point in a distribution network should not exceed. The planning levels on the harmonic voltage distortion and the harmonic assessment methodology for the connection of new load and generation are specified in Engineering Recommendation G5/4-1.

As part of this PhD, the author undertook an industrial placement at E.ON New Build & Technology Limited (former E.ON Engineering) to carry out an assessment of harmonic impacts in the Skegness distribution network as a result of the proposed wind farms. A technical report provided for E.ON following the assessment was delivered. It showed substantial increases in harmonic currents following connection of DFIG wind turbines. Brief details of the harmonic assessment project are presented in Appendix D.

## 2.6 A Transition towards Smart Distribution Networks

The increased connections of renewable and distributed generation have created a range of technical and non-technical impacts on the existing distribution networks. Specifically, the technical impacts have concerned the DNOs with the need to maintain security of the network operation as well as to allow increased volumes of DG connections. As a result, the passive operation of the existing networks that have become a limitation against the DG penetration requires a transformation. In this context, active or smart distribution networks are a new concept that could overcome such constraints, improve the network performance and raise the actual DG capacity that can be connected. Therefore, the transition of the distribution networks from passive to more active can potentially provide a long-term solution to accommodate future DG capacity integration. Currently, there are a number of active network designs and smart control schemes being developed worldwide. Amongst those control solutions, the concentration has been placed to the voltage control and thermal overload management schemes where this research lies within. Detailed literature and discussions of the transition from passive towards smart distribution networks and key examples of existing active control schemes follow in Chapter 3.

## 2.7 Chapter Two Summary

In this chapter, a detailed literature survey on distributed and renewable generation has been presented. Renewable distributed generation has received great attention worldwide. Advances in research, development and technology have enabled the use of various clean, renewable sources to generate electricity and in a range of output capacity, i.e., from small-scale generating units to large and commercial scale generating plants. Despite the increasing penetration of renewable DG in distribution networks, the passive characteristic of the networks have placed a limitation on the capacity of DG that could actually be connected. This challenge has stimulated the need for a transition in how existing networks should be operated. While there is still no clear solution to this, the concept of smart distribution networks is promising.

# Chapter 3

# Active Distribution Network Management

## 3.1 Introduction

This chapter presents a literature survey of active distribution networks, with a particular outlook on the UK activities. The technical impacts of increasing distributed and renewable generation in the distribution networks have become a major challenge to the network participants. DNOs are seeking innovative solutions that can surpass the passive operation of the distribution networks in a more active manner to avoid network reinforcement costs. The new concept of active (or smart) network management (ANM) is likely to provide network security but also to improve network capability and operational performance such that the DG connection capacity can be further facilitated. Since the beginning of this research until the time of writing up this thesis, a range of active control schemes have been developed and trialled with a few implemented. The evolution of active management for distribution networks focusing on the UK activities including those under trial, pilot and implementation are presented in this chapter. Whilst the term active distribution network is predominantly used in this thesis, the term smart distribution network is also used and both terms are interchangeable.

The chapter begins with a definition of Active Network Management. The control concepts that form a basis for ANM are presented. Key examples of existing ANM in the UK with a specific focus on voltage and power flow constraint management are examined. The potential risks and benefits associated with ANM are also addressed. An introduction to Smart Grids, a similar conception to the smart distribution networks is presented. Finally, views of recent smart grid activities in the UK, Europe and US are discussed.

## 3.2 Active Network Management: A Definition

Prior to describing the characteristic of ANM, it is important to clarify the denotation of the term ‘active’ as appears in the literature. Traditional electricity distribution networks have been structured to supply power from high voltage transmission systems to lower voltage consumers as its primary role where the level of DG penetration across the network is usually trivial. This has long been recognised as passive operation of the networks. However, the connection of DG has been growing and has changed the role of the passively operated networks to become active by means of allowing power generation closer to the demand point. This in turn causes bidirectional flows of power when the generation exceeds demand. In this context, the term ‘active’ exists to describe the distribution networks that are connected with renewable and DG units to supply power in their vicinities.

Distributed and renewable generation can provide a number of supports for the distribution networks in terms of the technical, environmental and economic benefits, for instance, providing low-carbon power, assisting in network losses reduction, maintaining reliability of supply, providing investment deferral of network upgrades, lowering electricity market price, enhancing energy efficiency and demand peak shaving [66-70]. Despite the range of benefits these new network participants can offer, the technical problems on the network operation as discussed in Chapter 2 become a concern for DNOs and limit further DG penetration. As a consequence of the need to mitigate those connection constraints, active management and active control technologies are being developed as a potential solution and alternative to traditional reinforcements or network upgrades that would otherwise be required. Amongst the existing active control technologies, ANM is one area that involves constraint management actions in active distribution networks. The definition and the characteristics of ANM are discussed in this section.

The Electricity Networks Strategy Group (ENSG) aimed to identify and address key issues of the long-term energy challenges in tackling climate change and ensuring secure, clean and affordable energy [71]. It defines ANM as [72]:

> "Devices, systems and practices that operate pre-emptively to maintain networks within accepted operating parameters. ANM may be compatible with automation of the network to speed supply restoration following an abnormal event, and increased visibility and control of the network to facilitate management practices."

This definition covers most key aspects of ANM. In addition, an ANM scheme as introduced by Currie *et al.* [73] refers to a solution that addresses the communications and control requirements for managing the technical constraints in real time. It is likely that in active distribution networks the communications between network operators, generation units and the control devices will play an important part in the deployment of ANM. In terms of time scale, operation of the ANM schemes can be based on real time, time of day, seasonal or contractual arrangements: the real time operation of active management schemes is emphasised in this thesis. Active management of distribution networks also provides an alternative method that optimises existing network operation, capacity and investment in order to accommodate more renewable and distributed generation [9]. In particular, the characteristics of ANM that intend to make the most use of network capacity, avoid expensive investment and increase the connection capacity of DG ties in with this thesis.

Active management of distribution networks can engage a number of activities which may include one or more of the following [72]:

- Voltage control
- Power flow management
- Equipment dynamic ratings
- Fault level management and protection
- Loss minimisation
- Network stability

- Frequency control
- Power quality
- Island operation
- Provision of ancillary services
- Demand side management
- Sensors, measurement and communications for network automation

In this research, the first two activities, i.e., voltage rise and thermal constraints mitigation, using active and reactive power flow management for real time operation in rural distribution networks are considered as the main challenge.

## 3.3 Active Network Management Spectrum

The need to lessen the impacts of connecting large volume of DG has stimulated extensive development of ANM, ranging from research-scale studies to commercial-scale implementations. Innovative ideas to evolve ANM are based on various methods, for instance, network parameter estimation to implement real-time corrective control, measurement and forecast of demand and generation for preventive control, agent-based network management using wide area communications and coordination, and regional data observation for remote management [11, 74-77]. Despite applying different strategies, most ANM activities share a similar control loop, i.e., collecting information, evaluating the network state and performing control actions. Through the process, one significant factor that can determine the capacity and the inferred economic benefits of an ANM scheme is the level of involvement and coordination between components within the networks. This factor can also be used as a criterion to distinguish an ANM scheme from those with similar control objectives.

Based on the degree of coordination, ANM activities can be categorised into three strategies as described by the active network management spectrum illustrated in Figure 3 - 1:

- Decentralised network management
- Centralised network management
- Semi-coordinated network management

This wide spectrum of active management can reflect the key characteristics of the ANM schemes. The main features of each area are described in the following subsections.


**Figure 3 - 1: Active network management spectrum**

### 3.3.1 Decentralised Control

Decentralised control in active distribution networks provides the control actions locally and only employs information and measurements available at the site. Decentralised control is particularly useful in areas with limited access to communications, on-line optimisation equipment and coordination between the sites and a control room. As a consequence, this strategy could offer an economic benefit by means of maintaining investment in such equipment at a minimum. Its local control feature could also avoid complexity of the control design architecture and risk of communication failure that are likely to occur in ANM schemes on a larger scale. On the other hand, the decentralised control strategy could put a limit on the capability to integrate other wide-area based control applications and enhance the overall performance of the networks. Examples of the decentralised control strategy include dynamic adjustment of voltage and power factor control mode of individual distributed generator for voltage control [78, 79], generation based-algorithm for power flow management and voltage control [80] and phase angle management using constrained wind farm power output [76]. In this thesis, the decentralised control strategy has been the main focus in developing the active management schemes to tackle voltage rise and line capacity overload constraints.

### 3.3.2 Centralised Control

Centralised control allows for real-time, multi-constraint active management to be performed in distribution networks under a supervisory or a coordinated system acting as a control centre. The system aggregates interactions of a number of network components, e.g., network control equipment, conventional power plants, DG units, storage devices, electric vehicles and demand and relies on coordination and information exchange using wide-area measurement systems and communications. Therefore, the reliability of communications and the coordination algorithms are crucial and will define the effectiveness of the scheme. The centralised management concept has been adopted in a range of active management applications, for instance, the Virtual Power Plant (VPP) system that can integrate a cluster of DG units, controllable loads and storage and enable them to be visible to the network operators in order to increase the renewable and DG connections and manage the power flow [81]. The VPP approach is also used to assist the energy markets to provide services and contracts where DG units are incorporated [82].

### 3.3.3 Semi-Coordinated Control

The semi-coordinated strategy combines the features of both the centralised strategy, i.e., managing the network from a supervisory control centre, and the decentralised approach, i.e., local control using DG capabilities, to perform constraint mitigation actions. Similar to the centralised control, this strategy uses coordination between devices associated within the networks, e.g., from the control centre to restrict the DG unit power output or to alter the tap position of the OLTC in response to the network constraints, but also allows local constraint management of DG unit where it is more cost-effective. Depending on size of the scheme, however, incorporating a number of components may lead to increasingly sophisticated system design and coordination which is usually undesired by the network operators.

## 3.4 Active Network Management Activities

Whilst security and reliability of the electricity networks are amongst the main concerns, ANM development has been of interest as being a solution to effectively manage the technical impacts of DG connection and to avoid high capital expenditures incurred due to network upgrades. Particularly for distribution network operators, ANM technologies are expected to be able to maintain secure and reliable access for DG penetration, but also provide automated network operation and allow greater potential of DG capacity to be connected. Future advanced ANM technologies will essentially involve measurement, communications and coordination devices between ANM and other components in the system, i.e., the transmission system, power generation plants and consumers.

Throughout the time of carrying out this research, a range of ANM activities have been created although to a great extent the development is still at the early stage. That is, most of the ANM-related projects have only concentrated at research level with few demonstrations and implementations. Since 2006, there have been a number of innovative designs and techniques registered as potential ANM schemes in the UK [83] with the most developed solutions being voltage control and line flow management. Those projects can also be categorised based on the active management strategies as discussed in Section 3.3, i.e., decentralised, centralised and semi-coordinated control strategies. This section will summarise and discuss ANM activities existing in the UK and worldwide that are most relevant. The survey will emphasise the solutions for voltage control and line flow management.

### 3.4.1 Voltage Management

Connections of DG in the distribution networks can alter the voltage. In particular, variable DG can cause undesired voltage variation and raise voltage to the statutory limits. A range of methods and technologies are being developed to mitigate voltage rise:

- Increase of conductor size or reconfiguration of network
- Installation of additional auto transformers or voltage regulators along the feeder to which DG is connected
- Active control of the OLTC transformers to reduce voltage at primary feeder
- Active power curtailment of DG
- Reactive power (power factor) adjustment of DG
- Installation of shunt capacitors for reactive power support
- Use of controllable loads
- Combination of any of the above methods

The first two methods may be considered the last option as they require high investment compared to the rest. Most of the methods found in the literature employ the centralised and semi-coordinated strategy whilst only a few adopt the decentralised concept.

**<u>Centralised voltage management by control settings of OLTC transformers</u>**

One of the simplest techniques to provide a centralised voltage management is to control the settings of the OLTC transformers. Voltage regulation in distribution networks are ordinarily performed by the OLTC transformers and the AVC relays at substations to maintain the feeder voltages downstream. The voltage reference value and the tap setting are preset according to historic or seasonal load data taking negligible account of power generation from DG. Hence, the centrally voltage management may be introduced by way of actively modifying the setting of the AVC relays upon the tap operation. Amongst the earliest and most innovative voltage control technologies developed in the UK is GenAVC™. GenAVC™, developed by White [11] at Econnect, is a centralised distribution network controller that controls the 33/11kV substation OLTC transformers to ensure all multiple feeder voltages beyond the substation remain within limits. The functional structure of the GenAVC™ is shown in Figure 3 - 2. The system is based on state measurements at remote locations, including the DG buses, via Remote Terminal Units (RTUs) and uses the collected information to estimate the voltages on the network in order to decide the control command to be sent to the transformers. It has been trialled at different UK sites since early 2005 and the results confirmed its accuracy and performance in estimating and managing the voltages in the network.

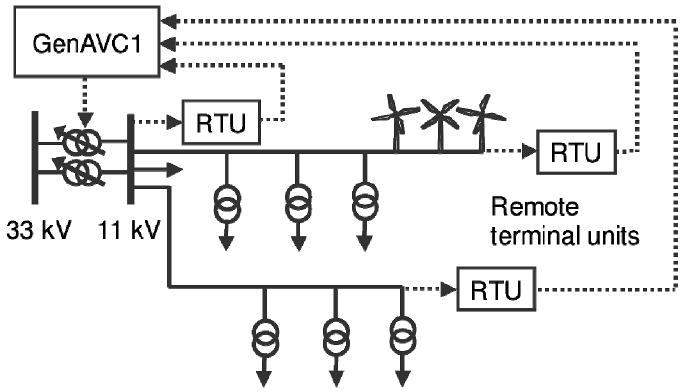



**Figure 3 - 2: Structure of the GenAVC™ system on an 33/11kV network [11]**

Another centralised approach to control the OLTC transformers is an Automatic Voltage Reference Setting (AVRS) technique, built by Li and Leite [84]. The system as shown in Figure 3 - 3 provides a real-time voltage reference setting over the tap actions of the transformers. The AVRS selects the maximum and minimum voltages from two or more voltage measurement points in the network and compares with the specified voltage limits in order to estimate a new voltage reference for the AVC relay. The AVC relay will then instruct the OLTC transformer to tap accordingly. The authors concluded that through the case studies the prototype performed the voltage management correctly and allowed more DG capacity to be connected.

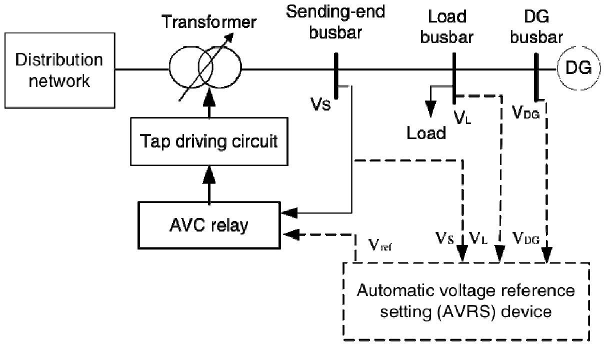



**Figure 3 - 3: Structure of the AVRS system [84]**

**<u>Coordinated voltage management using combination of methods</u>**

An algorithm employing a combination of various voltage support solutions based on a coordinated control rule has also been developed. The Distribution Management System (DMS) controller developed by Strbac *et al.* [85] focuses on the management of voltage rise in rural distribution systems with embedded generation. The DMS controller, depicted in Figure 3 - 4, performs its operation in two main functions: state estimation and control scheduling. The state estimation receives the network electrical parameters (P, Q and V), network topology, loads models and real-time measurements as its inputs to produce a network state estimation. The control scheduling then uses this estimation to calculate a new set of control values that will instruct network devices, e.g., AVC relays of OLTC transformers and DG units, to optimise power flow while ensuring all network constraints are met. By obtaining the network flows and voltages from load models and real-time measurements as inputs, the DMS will generate associated control values, i.e., tap positions for OLTC transformers and generator dispatch in order to instruct the transformers and the DG units. For single-transformer systems, the instruction will be directly given to the AVC relays and in case of multi-transformer system, the DMS will command the set point of the master in order that the transformers perform their actions in master-follower configuration. The DMS controller can also control by disconnection and reconnection when it senses any unacceptable voltage level. For embedded generators, the DMS constrains the outputs by producing set points for the automatic voltage regulator (AVR) and the governor and signals to supervisory control and data acquisition (SCADA) systems.

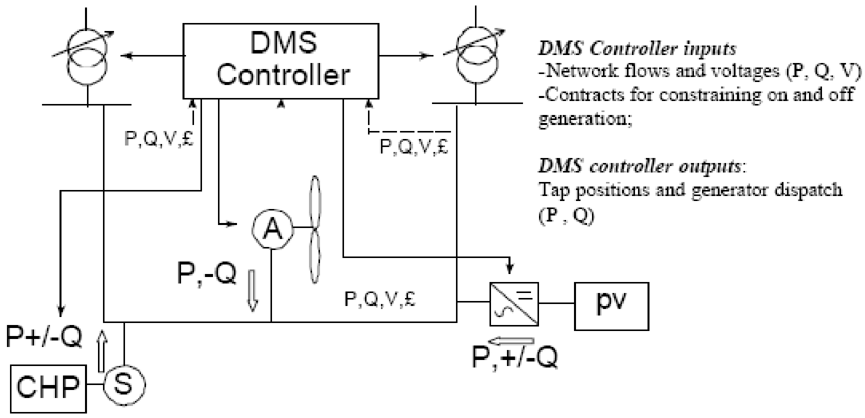



**Figure 3 - 4: Structure of a DMS controller [85]**

Viehweider *et al.* [86] develop a voltage control algorithm using a combination of existing voltage control. The algorithm is based on interval arithmetic and state machine methods to define the order of intervention. The solutions include, in order of priority, actions of the OLTC tap, DG reactive power management and DG active and reactive power settings in which the control actions will take place by following these states. Optimisation is also applied to the latter two solutions. The authors have demonstrated that the algorithm is able to overcome the voltage variation problem in the distribution network and can account for the inaccuracies due to unknown demand data and measurement errors and the nonlinearities of the network models.

Liew and Strbac [87] present several voltage constraint management strategies for wind farms connected to rural distribution systems for worst-case conditions, considering maximum demand and minimum generation. The voltage control strategies include active generation curtailment; reactive power compensation and area-based OLTC coordinated voltage control. An OPF-based tool with an objective to minimise active generation curtailment cost was formulated to value the benefits and costs of the proposed strategies. Case studies of incremental wind generation output on an 11kV rural distribution system using different voltage control applications were carried out and evaluated based on net energy export and power loss due to curtailment. The authors concluded that, according to the results, wind generation could considerably be increased when implementing the proposed voltage control applications in particular using the area-based OLTC control. The impact on network losses was insignificant at low wind penetration level however this would become an issue when the penetration level increased.

Xu *et al.* [88] use a case-based reasoning technique to deliver real-time voltage control by matching specific voltage problems with available control solutions. There are several voltage control actions that the DNOs may utilise, for instance, OLTC control, power output and power factor control, energy storage and network reconfiguration. Considering the voltage variation problem in severe circumstances, a single solution may not be sufficient whereas a combination of methods could overcome the voltage impact more effectively. The proposed technique selects the corresponding voltage control solutions to match the voltage problems using similarity measures of situations to the successful solutions that are stored in a case library. The authors demonstrated that the technique reveals effective performance to cope with voltage variation problems on a radial distribution system. This voltage control technique is part of the AuRA-NMS (Autonomous Regional Active Network Management System). The system will be presented in detail in Subsection 3.4.3.

**Decentralised voltage management**

A series of decentralised approaches have also been proposed in the literature. Kiprakis and Wallace [78] introduce two voltage control schemes that utilise local real-time measurements of synchronous generator's terminal voltage to specify the reactive power output from the DG. The first scheme was a hybrid system that intelligently operates the DG in two modes based on a set of rules involving the measured terminal voltage: power factor control and voltage control. When the measured voltage is within safe upper and lower limits, the DG operates normally under power factor control (unity or specified power factor). The DG switches to voltage control mode when the voltage would otherwise exceed the limits. This work has been a fundamental basis for the decentralised control schemes presented in this thesis. The second strategy uses fuzzy inference logic to create a smooth function to define the target reactive power setting at a given voltage level. Both schemes operate within the power factor capability set by the machine specifications.

Tran-Quoc *et al.* [13] develop a real-time, auto-adaptive voltage regulator for multiple DG units connected to the same substation. The adaptive controller uses a voltage deadband system to determine the optimal amount of active or reactive power required from one specific or more DG units in order to perform voltage control. The proposed deadband system consists of three states of voltage levels defined within the upper and lower voltage limits: normal, perturbed and critical states. Under the perturbed state where the voltage exceeds the specified maximum voltage limit, the control action is taken by the DG operating in voltage regulation mode and the optimal amount of reactive power is determined. The critical state is when the reactive power of DG reaches its limit and hence the DG operates in active power regulation mode to optimally adjust its active power generation.

Scott *et al.* [89] propose a technique to control customer load in order to manage excess voltage at periods of high wind generation. When voltage rise occurs, the technique increases controllable consumer demand particularly storage systems, e.g., thermal storage heaters and hot water systems, such that surplus energy is consumed to reduce the voltage rise. The authors showed the effectiveness of the technique by comparing to other existing voltage regulation schemes (i.e., change of connection point, network reinforcement, constraining active power and power factor control). Whilst the voltage control performance of each scheme was comparable, the economic viability was distinct. The load control technique required high capital cost but could provide a cost-effective option only when comparing to connection point changes and system reinforcement. The use of controllable demand or demand side management to provide voltage control is also being developed [90-92].

Fila *et al.* [93] develop a decentralised voltage control using similar principle to the GenAVC™, i.e., active control of OLTC settings. Called the SuperTAPP n+ relay, its technical arrangement is depicted in Figure 3 - 5. The system uses additional current measurements on the feeders accommodating DG units and the possible load share ratio between feeders without DG. This technique gives the ability to estimate the DG power output in remote locations as well as the voltage rise at the point of connection during the times of maximum DG export. Appropriate voltage set point for the AVC relay can then be evaluated as a consequence. The technique was tested in a realistic distribution network operated by EDF Energy (now UK Power Networks) [93, 94]. The results showed its performance to manage the voltage rise during minimum demand and that the technique was able to allow higher DG capacity to be exported. Using only the current measurements at substation, the scheme could avoid complicated communication tools. However, it greatly relies on substation measurements, a network emulation model, historical SCADA data, state estimations of voltage and DG exports and approximations of the load share ratio. This may cause the scheme to be subject to errors. Moreover, the scheme may not be able to immediately discern the instantaneous voltage rise associated with variable power injections such as wind.

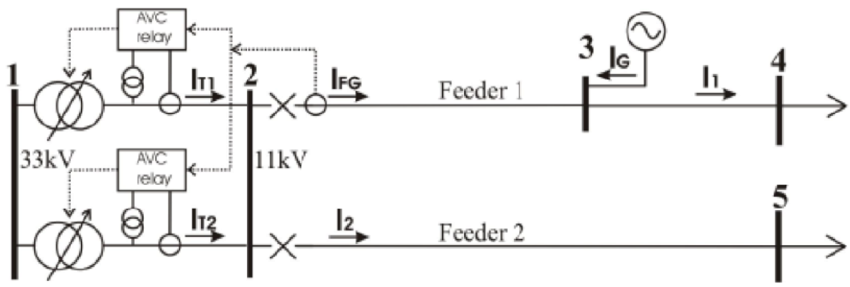



**Figure 3 - 5: Arrangement of the SuperTAPP n+ relay [93]**

### 3.4.2 Line Thermal Management

Overhead lines and cables in typical distribution networks are capable of conducting electric current up to a limit based on either conductor temperature or sag temperature due to heat losses. This capability refers to the term ‘current-carrying capacity’ of the line and is affected by various factors, for instance, conductor size, amount of current flow, line resistance, wind speed and direction and surrounding temperature. Seasonality also affects this capability with line capacity higher in winter than in summer as the ambient temperature is lower. In distribution networks, the sizes as well as capacities of lines and cables were designed such that the expected power flows will not breach the limits. The planning already takes into account future load growth; nonetheless, it has disregarded new generation capacity and DG. In order to allow further DG penetration without reinforcing the network, the best possible solution is for the network operators to be able to dynamically reduce the line flow when required. As will be presented in this section, a number of line flow management techniques have been developed to increase the DG capacity. The techniques presented in the literature adopt centralised control to manage contributions from multiple DG units within the vicinity.

Ault *et al.* [12] and Currie *et al.* [75, 95-98] develop an Active Power Flow Management (APFM) scheme to actively manage the power flow constraint in the context of multiple DG units connected to distribution networks. The well-known scheme has been designed and deployed in a real distribution network on the Orkney Islands, owned and operated by Scottish and Southern Energy (SSE). It manages power flow congestion of renewable generating units in order to maximise the generation capacity yielded. The control philosophy is based on the principle of connection access considering three generating groups: firm generation (FG), non-firm generation (NFG) and regulated-non-firm generation (RNFG). FG is the capacity level allowed for generators to operate at rated power output during an outage of the largest rated capacity circuit [95]. Beyond this capacity level, generators can be connected but will be required to immediately trip if a first circuit outage occurs to ensure security of the network; this is called NFG capacity level. RNFG are the generating units connected in addition to the FG and NFG capacity levels mostly to serve demand variation. RNFG usually refers to renewable generating units. The APFM scheme is applied to logically trim and trip the RNFG units in real-time based on measurements of the power flow exports against a threshold in order to maintain the line thermal limits as well as to maximise the connection capacity from renewables. The amount of RNFG units to be trimmed or tripped will be determined according to the connection arrangement. That is, the last unit connected to the network will be the first one to react. This is so called a 'Last-In-First-Off' (LIFO) principle [12]. The APFM scheme has been recently commissioned as the first commercial ANM technology deployed on the Orkney distribution network with several renewable generating units participating. Performance of the APFM has been reported by the authors as providing effective, secure and reliable accommodation of DG and can allow further renewable units to be connected [98].

A power flow management method called ‘dynamic line ratings’ or ‘dynamic thermal ratings’ has been of increasing interest to many researchers and network operators [99, 100] as a means to enable DG connections. A dynamic line rating scheme developed by Yip *et al.* [99] provides a real-time mitigation of congested active power flow through overhead lines and cables in distribution networks and to better utilise the actual available capacity of lines. The method uses local weather measurements to derive the real-time loading capacity of lines from the current weather conditions. A device called a ‘power donut™’ is fitted to the line to calculate the conductor temperature for comparison and validation with the measured weather conditions. In this way, the line capacity can be constantly monitored and the required control of DG power output can be performed accordingly. The method has been implemented to monitor and manage the power flow in the 132kV overhead line between Skegness and Boston (East of England) and the results reveal that more wind generation can be connected compared to using the fixed (static) line ratings.

Ochoa *et al.* [100] employ a multi-period AC Optimal Power Flow technique to adopt different control strategies, i.e., coordinated voltage control and dynamic ratings, in a different aspect to that developed by Yip *et al.* Instead of using the dynamic ratings to manage the power flow congestion in real-time, the authors propose the method as a planning tool for the evaluation of the maximum capacity of wind generation that could be connected. As for the dynamic ratings, the current carrying capacity of overhead lines is calculated by assuming different temperatures according to seasons over a period of one year. Based on the case studies, the authors have demonstrated that, taking into account the advantage of wind cooling effect, the dynamic ratings could increase the capacity of wind generation in comparison to the use of static ratings. With the incorporated voltage control and the dynamic ratings, the capacity of wind generation connection could be further increased.

### 3.4.3 Multi-Constraint Management

As presented in Sections 3.4.1 and 3.4.2, a number of active management methods have been developed to deal with one individual constraint, either voltage rise or line overload. However, such methods may not be able to provide sufficient control actions under severe situations. While the interactions between discrete control methods and the DG capacity present on the distribution networks are becoming more complex, a control system that is able to perform multiple constraint management is required. As presented in the literature, multiple constraint solutions mostly adopt semi-coordinated and/or centralised control approaches as such solutions require some coordination and communication between central control and DG units.

Davidson *et al.* [74, 101] introduce an 'Autonomous Regional Active Network Management System' (AuRA-NMS) as an intelligent system that integrates four main control tasks, with a number of methods used in each task, in order to cope with multiple network issues: steady-state voltage control applying constraint programming for voltage control and case-based reasoning (described in [88]) approaches; automatic restoration; line power flow management applying constraint programming and Optimal Power Flow (OPF); and network optimisation strategies in real-time. The technology was developed by a collaboration between seven UK universities, two DNOs (UK Power Networks and Scottish Power Energy Networks) and ABB (major manufacturer specialised in power and automation technologies) [101]. AuRA-NMS operates based on multi-agent systems technology that defines each of the control functionality as an agent, for instance, a voltage control agent will react within its vicinity to maintain the voltages limits, under the provision of an agent management system (AMS). Agents will also communicate with each other and with existing devices in the networks so as to update the resulting control actions; hence communication systems need to be reliable and robust. AuRA-NMS has recently been tested in medium voltage networks operated by the two different DNOs in order to investigate the operational performance, potential problems, advantages and disadvantages of the distributed and centralised control approaches embedded in the AuRA-NMS functionality. The aim is that future deployment of AuRA-NMS will provide flexibility and extensibility to a range of different network characteristics [101].

There are also a few control solutions present to provide active management of voltage variation as well as the thermal overloads. Boehme *et al.* [18] develop sequential time-series analysis of renewable DG types including wind, wave and tidal generators in order to examine the opportunities of capacity connection, level of curtailment and the subsequent economic impact. The technique applies optimal power flow subject to voltage and thermal constraints by employing active generation curtailment to maintain the voltage and line thermal limits. The case trials were simulated in the Orkney Island Distribution Network. The technique can be seen as a first-level analysis to be carried out during the planning stage, providing values to facilitate renewable DG connections and estimate the degree of curtailment expected.

Ochoa *et al.* [76] develop an angle-constraint management technique to overcome voltage rise and line overload using the information of current and voltage phase angle obtained from Phasor Measurement Units (PMUs) installed at substations and at DG connection points. By constantly comparing the angle differences between measured and reference (fixed angle) values, where the angle difference exceeds the angle limit then active power control is applied in order to reduce the voltage rise or the congested line capacity. The use of synchrophasor measurements provides for active management of multiple constraints and has been shown to allow more energy export from DG.

## 3.5 Benefits and Risks of Active Network Management

This section discusses the potential benefits and risks of active network management schemes. The main benefit of active network management is in enabling better utilisation of the available network headroom to facilitate renewable DG units while making sure the network operation is secure and reliable [98], taking into account the diversity and growth in demand.

As presented in Section 3.4, a number of active management techniques employ centralised and semi-coordinated approaches where measurement, communication and coordination activities are involved. The utilisation of additional data measurements and communication and coordinated control logic between central control and the regulated devices in active distribution network allow advantages against the locally controlled based schemes to be gained in many ways. Adequate data sensors and measurements will support detection of network constraints and the corresponding control actions more immediately and accurately. For instance, the centralised voltage management that utilises real-time voltage monitoring systems distributed in the network will have better visualisation of voltage behaviour at critical points. Hence, the voltage problems can be overcome more precisely as the system can cover voltage variations that may not be detected by typical AVC systems at substations.

In terms of large-scale development and implementation, the measurement and communication infrastructure employed in the active management schemes allow for other forms of active network management to be adapted and extended widely into remote areas in the networks. Adaptability and extendability are important in planning for future growth in DG connections in the long run. This presents an advantage over the locally-based active management.

Despite the technical benefits of active management using centrally-controlled and semi-coordinated approaches, the dependency on measurement devices and communication links may inevitably bring about risks to the distribution network operation. Especially, the control activities that involve signalling and data transfer based on high level, two-way communications such as the ANM schemes presented in [98] and [101]. The performance of the control is directly affected by the quality, reliability and robustness of communication links, measurement and estimation systems, data analysis and processing time. Whether the ANM scheme is real-time automatic or requires an on-line human interface, a back-up system for substitution during loss of communication or data processing and signalling system failure may be necessary to ensure the control scheme can continue its function and avoid unexpected interruptions.

Decentralised control by definition only makes use of existing and available network data as well as the generator's capability for control execution. This has a benefit for the network operators in that the upfront costs that might be incurred from network reinforcement or additional measurement and communication systems can be reduced. The approach can also eliminate risks due to the dependency on interfaced communication and measurement systems with a central controller. Nonetheless, the operational performance of a local control may be modest compared to a wide-scale active management schemes but they might potentially provide adequate responses to overcome the constraints at least in a short term.

In terms of commercial arrangements and financial viability, the decentralised control approach may offer active management users a more economic choice provided that the extra cost of using communication and sensing systems is not required. However, depending on the type of constraints and the corresponding active control technologies, the control performance and benefits gained may outweigh the investment. As such, thorough evaluation of the trade-offs between potential benefits and risks incurred according to some related parameters, e.g., network compatibility, investment, operational performance, must be considered. In this thesis, evaluation of the performance and economic trade-offs of the proposed control is also taken into account.

Notwithstanding the active management approaches along the spectrum, the benefits that the ANM solutions will bring are recognised. From trials, the next step forward is for the solutions to become commercially implemented. This is inevitably where real challenges exist and must be addressed. Such key barriers and risks of ANM solutions include [102]:

- A lack of readiness in commercial arrangements, standard business contracts and regulatory frameworks for ANM, causing a delay in implementation and a lack of confidence for DNOs and DG developers;

- A lack of standard requirements regarding active power curtailment and reactive power support of DG;

- Safety and continuity of supply concern due to a lack of experience with ANM operation;

- Insufficient drivers and clear investment opportunity that encourage ANM schemes to be brought towards widespread adoption.

## 3.6 Smart Grid

Smart Grids have recently been put forward in the power industry worldwide as a new dimension for future electricity networks. Smart grid may simply be defined as the electricity system that is smart however the term can be described in many different ways depending on for instance operational purposes and network characteristics. As present and future electricity systems will involve significant changes to the generation and demand patterns, smart grid will be required as a means to supervise such changes in a smart, modernised, secure and reliable manner. More importantly, efforts to develop smart grids are driven by five main purposes [103] for long-term deployment: firstly, to enable the production and supply of electricity more cost-effectively; secondly, to allow consumers to be informed with necessary information such as electricity price and their energy-use behaviour in order to obtain the most efficient and economic energy consumption; thirdly, to encourage renewable DG integration; fourthly, to enhance the electricity systems' security and reliability; and fifthly, to support the growing use of electric vehicles in the coming decades to reduce dependency on oil.

From the author's viewpoint, 'Smart Grids' involve several active components in the electricity distribution networks that will interact with and influence each other to support the integration of renewable DG and advanced loads such as electric vehicles. The active components are active loads, which engage 'Demand Side Management' or 'Smart Metering', energy storage, automation and active management functions. In this context, ANM can therefore be regarded as one branch within a smart grid. Smart grids also involve full-scale measurements and communications platform such as SCADA, sensors and monitors via RTUs to be expanded across the networks. With the use of coordination, communications and interactions between branches, the functionality of smart grids can be characterised as being a centralised control.

At the time of writing this thesis, smart grid is still under development and has not been deployed on electricity networks. For the meantime, there have been several functional designs in an attempt to describe the concept of smart grid. An example of a smart grid model is depicted in Figure 3 - 6. The conceptual model, presented in [103], comprises all network participants, i.e., generation, transmission, distribution, customer, electricity markets and service provider, under the supervision of network operators where information is exchanged and/or updated between each element in real-time. The model also heavily involves complex communication links and coordination which presents the key aspect of smart grid. The use of advances in wireless communication networks to mitigate problems of distant communication such as real-time traffic and to enhance reliability and efficiency of data transfer has been introduced in [104].

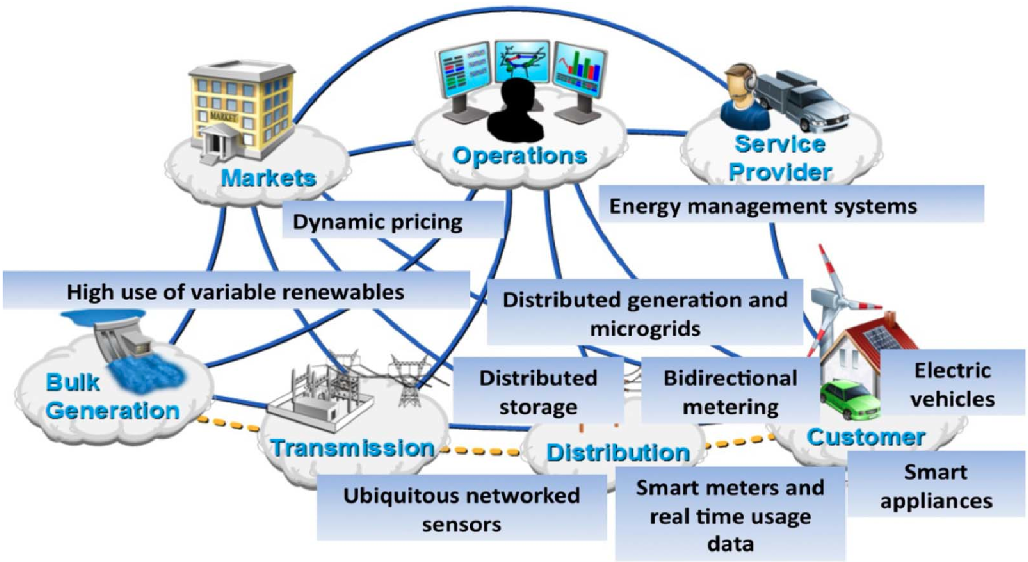



Figure 3 - 6: Conceptual model of a smart grid [103]

## 3.7 Smart Grid Activities in the UK, Europe and US

In the UK, the advanced smart grid technologies appear largely as active network management. The technologies will enable safe and economically feasible connections of DG by improving network visualisation in real-time and providing instantaneous constraint management where advanced monitoring, communication systems and automated and innovative control are deployed. There are also a number of active network management projects under the IFI and the LCNF mechanisms that feature smart grid's perception [105]. Another aspect of the smart grid involvement in the UK is associated with customer participation. The smart electricity and gas meters framework, mandated to be rolled out by 2020, will provide customers with information on real-time gas and electricity consumption and assist them to better manage their energy demand and the corresponding price as well as to improve home energy efficiency [106].

In Europe, the smart grid initiative was formed in 2005 under the European Technology Platform (ETP) contributed by representatives from the industrial sector, transmission and distribution network operators, academic researchers and regulators to create a vision for European electricity networks towards 2020 and beyond. In summary, the vision is to ensure flexibility to meet customers' needs and respond to network challenges, accessibility of connection to all new low-carbon generation, reliability of the electricity supply and best value of network innovation technologies and energy efficiency management [107]. This has stimulated a number of smart grids activities where, in the long term, six aspects are to be achieved: optimising grid operation and use, optimising grid infrastructure, integrating large scale intermittent generation, information and communication technology, active distribution networks and new market places, users and energy efficiency. The readers may find more details of these priority plans of Europe's future electricity networks in Ref. [108]. For the near term, the activities associated with smart grids within the European nations will particularly involve more actions from consumers, that is, to promote micro generation penetration in low voltage networks where consumers also act as potential producers (known as ‘prosumers’ [109]) and to employ new technologies that offer active demand response and demand side management options for consumers to optimise the energy exchange, efficiency and diversity.

The development of smart grid in the US has been based on the need to maintain security and reliability of the electric transmission and distribution grids that are interconnected across large areas [110]. This is evidently seen by a few major blackouts and interruptions events, which have resulted in undesirably expensive losses to the utilities and customers. The cause of such blackouts and interruptions is due to the continuing increase in the energy needs following the nation’s population growth. Although, there have been plans to extend the electric grids in order to accommodate such peak demand, the existing old and centralised architecture has made the grids difficult to extend or reinforce. The smart grid development will provide a means to improve the grid security and reliability, minimise the frequency and interval of power outages and manage power flows congestion. Smart grids in this context therefore involve advancements in making the grids more visible and manageable. For instance, Advanced Metering Infrastructure (AMI) will allow interruptions to be detected and the grid operated more effectively [111]. More than 7 million AMI smart meters have already been installed and operated in the US [111]. Automation in transmission and distribution assets, e.g., advanced sensors, switches, and communication tools have also been adopted. Such smart grid deployments, in addition, are supported through a number of schemes already in place. The Smart Grid Investment Grant and the Smart Grid Demonstration programmes are the two main initiatives to accelerate innovation and modernisation of the transmission and distribution systems and to encourage investment in all aspects of smart grid including technologies, methodologies and devices [112]. This is similar to the IFI and the LCNF schemes in the UK.

## 3.8 Chapter Three Summary

This chapter presents a literature survey of smart distribution networks focusing on the methods to overcome the voltage rise and line thermal overload problems. As discussed, most existing ANM approaches contemplate the solution to one particular constraint, i.e., either the voltage rise or line power flow. Although, there have been a number of solutions to tackle multi-constraints, at the time of starting this research, very little work considered the decentralised control of active management of both issues in real-time. This thesis therefore takes further steps to develop a control scheme that is able to actively manage one or multi-constraints occurring simultaneously in weak distribution networks connected with variable wind generation.

The evolution of passive network operation to become active is complicated and may involve several changes to the network infrastructure. Comprehensive trials of such active schemes are also required to ensure the compatibility and effectiveness before implementing into the networks. Active management that can offer full and adaptive control options for the distribution networks such as those in the concept of ‘smart grid’ are also expected. At time of writing this thesis, there has not been a full deployment of the smart distribution networks in the form of active voltage and thermal overload management. Amongst other innovative control schemes, this research could also provide a significant contribution to smart distribution networks.

# Chapter 4

# Decentralised Voltage and Thermal Constraint Management

## 4.1 Introduction

In the previous chapter it was shown that active distribution network management can be categorised across a spectrum covering decentralised control, semi-coordinated control and centralised control. The main focus of this research was to investigate decentralised control schemes to manage voltage rise constraints. The work substantially extends previous work [15-17, 78, 113], conducted within the Institute for Energy Systems (IES) at the University of Edinburgh. It developed an 'intelligent', local voltage control scheme using the ability of a generator (or a DG unit) to adjust its power and is discussed in Section 4.2. Connection of DG in rural distribution networks is also subject to thermal (or power flow) constraints. As these are one of the most significant issues, innovative control schemes to overcome the voltage rise as well as the thermal overload problems associated with the connection of DG are required.

This chapter provides a progressive set of control schemes designed to tackle voltage rise and thermal constraints. Firstly, the voltage control scheme developed in previous work is discussed. The modelling specifications and considerations for the developed scheme are provided. Then, the control algorithms of the decentralised voltage management ('V Mgt') and the thermal constraint management ('T Mgt') sub-schemes are presented. For each sub-scheme, different control methods and settings of the actual control mechanism are identified, followed by validations of their control mechanisms. Operation of joint decentralised voltage and thermal management is described. Case study and performance assessments are presented.

Finally, the chapter summarises the methodology, application and implementation of the proposed voltage and thermal constraint management.

## 4.2 Detailed Review of Previous Work

As discussed in the literature survey, Wallace and Kiprakis [15], Kiprakis [16] and Vovos *et al.* [17] presented an intelligent voltage control algorithm that used the generator's ability to adjust its power factor to manage voltage rise in weak rural distribution networks. The previous work concentrated on developing a transient (dynamic) model of generators and voltage controllers to improve steady-state voltages. In this chapter, details of the generator's model and the voltage control algorithms are outlined. An indication of how this research extends the previous work is also presented.

### 4.2.1 Generator Dynamic Models

A generator's behaviour can be classified into three operational time frames: sub-transient, transient (dynamic) and steady-state (static) periods [114]. The sub-transient period describes short-period transient effects during the first few cycles of a generator start-up. The transient period depicts the generator electrical dynamics including responses to small disturbances and faults. Steady state refers to the state where the system voltage at the connection point remains constant in magnitude and frequency and is not altered by disturbances [114].

In the previous work [16], two types of generators' dynamic models were used: hydro and wind energy conversion systems. The work was based on transient stability studies and steady state power flow studies using dynamic models of the power system, generator and controller.

The small hydro generation and wind energy conversion systems consist of a number of small parts and their dynamic models were built using Simulink in MATLAB. The wind energy conversion system comprises blade pitch angle controller, speed controller, voltage/reactive power controller, real power controller, doubly fed induction generator and power electronic converter.

The power factor control mode of the generator was also modelled as illustrated in Figure 4 - 1. In this mode, the generator runs with a fixed power factor and this is considered as a normal operation for simulation studies.

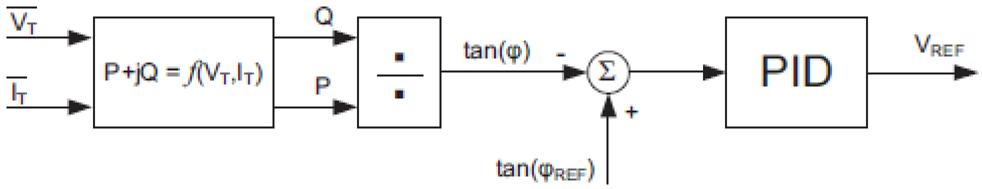



**Figure 4 - 1: Simulink block diagram of power factor controller [16]**

While the dynamic models were well used, much of the validation was for steady state simulations. As such, in this research, the high order dynamic model of the generator is not involved. Instead, static power flow studies (as will be discussed in the next section) are used to examine the system voltages and power flow in steady state and utilises time series data of generation and demand.

### 4.2.2 Intelligent Control of DG

The intelligent control, termed Automatic Voltage Power Factor Control (AVPFC), combined the advantages of AVR (Automatic Voltage Regulator) and PFC (Power Factor Control) modes. The operational scheme of the AVPFC is presented in Figure 4 - 2. The DG operates along the thick, dashed line. Under normal operation when voltage is within minimum and maximum limits as defined by the DNOs, the DG unit operates in PFC mode at a constant power factor ($PF_{PFC}$). When voltage approaches the limits, the PFC mode is deactivated and the AVR instead takes a control action. In the AVR mode, the DG unit produces or absorbs reactive power to support voltage but is restricted to the over and under excitation limits that are defined by the minimum and maximum operating power factors (i.e. $PF_{min}$ and $PF_{max}$, respectively). The aspect of using the dual operation between power factor control and voltage control modes has been brought forward and extended in this thesis.

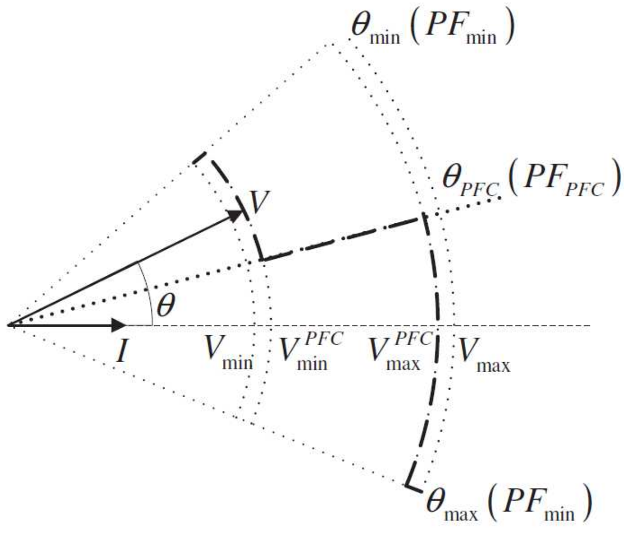



**Figure 4 - 2: AVPFC operational scheme [113]**

The Simulink block diagram of the AVPFC is shown in Figure 4 - 3. It consists of two nested loops: (i) inner loop to execute voltage control at the generator's terminal according to a defined voltage set point and (ii) outer loop to adjust the generator's operating power factor according to a power factor reference (*tan($\varphi_{ref}$)*).

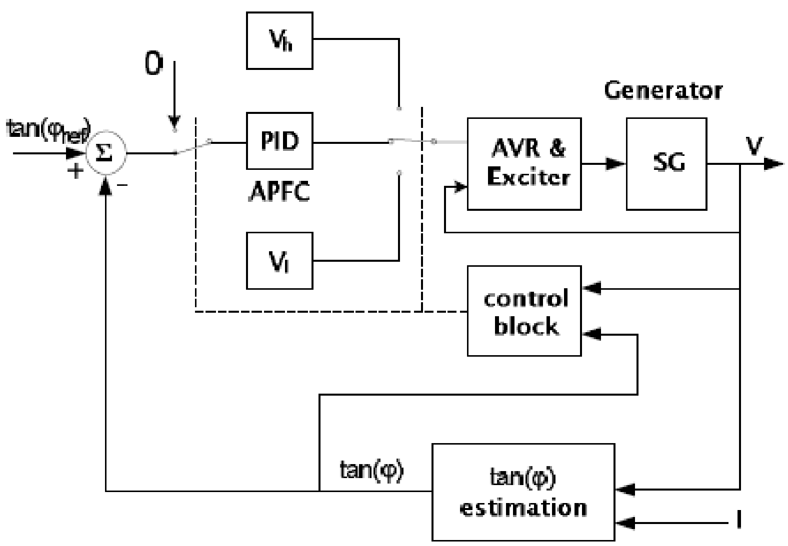



**Figure 4 - 3: AVPFC dynamic block diagram [113]**

## 4.3 Specification, Modelling Considerations and Overview of Decentralised Control

In modelling a control scheme for active (voltage and thermal) management and carrying out testing and simulation studies, there are a number of factors needed to be considered. In this research, specifications on the following factors are required:

1) forecasts of demand and wind data;

2) power system study (dynamic or steady state);

3) continuity of control operation (discrete or continuous);

4) generator (DG) type;

5) threshold to identify constraints (deadband or pure statutory limit);

6) critical generation capacity (maximum possible fit & forget capacity);

7) flexibility and extendability of scheme.

**Forecasts of Demand and Wind Data**

The developed control scheme (for both voltage and thermal management) is primarily associated with the regulation of active and reactive power of the DG in order to perform real-time corrective control. In this context, the information about wind as well as demand forecast at the site is significant as it determines how much wind power output is to be produced for the next time period. This affects the regulated active and reactive power in response to the constraints. In this research, two assumptions regarding wind resource and demand forecasts have been considered:

A. **Perfect Forecasting:** ideal situation where wind and demand forecasts of the next time step are known;

B. **Persistence Forecasting**: wind and demand forecasts are not available and all control values are estimated based on current states. This condition mimics the real control environment that is seen in most distribution network connected DG (wind farms).

The ideal situation (perfect forecasting) was used largely in the beginning of the research on voltage management. The control scheme has also been extended (to deal with the thermal overload constraint) using the same forecast assumption. Then, the voltage and thermal management is developed by considering the actual (real) situation that the next time step wind and demand forecast is not available (persistence forecasting). The voltage and thermal management scheme with persistence forecasting was developed later and provided a significant contribution to this research. The progression will be presented later in this chapter.

**Power System Study**

In general, power system modelling and analyses can be performed in two major categories: transient (dynamic) and steady-state (static) studies [114]. Selection of the power system analysis type is important and has to be justified as it affects the simulation time and the types of data required for network, demand and generation including the control scheme. As presented, the previous work [16] was conducted using very detailed dynamic model block diagrams of power system components including the controllers and the steady state voltage studies were in very high resolution, e.g., seconds. The dynamic model is efficient for transient stability study (e.g., dynamic response to large disturbances or faults) but does not offer useful information of the system performance in the long run [16]. For comparison and improvement purposes, this research has been carried out in steady state and all variables (i.e., network parameters, voltage, line flow, demand and active and reactive power) are static and continuous on a larger-scale time step, i.e., hour or minute time step, where the detailed dynamic block diagrams are not required. As the developed control schemes are associated with frequent adjustment of active and reactive power of wind, modern wind turbines are mostly capable of fast adjusting active and reactive power according to predefined set points [38, 115]. Therefore, the time series data (characterising the variability effect of demand and wind) and simulations in an hour or a minute step are possible. In addition, the developed schemes are expected to capture the variability effect of wind and manage the constraints in real time and over a continuous period, the use of a larger time scale can reduce the simulation time while achieving comparable control performance. Hence, the control schemes operating in steady-state is also suitable. The simulation time issue is also the case for high resolution time step that can as well be time consuming. However, for a generator (not necessary wind) that is able to promptly adjust its power and reactive power output (in seconds), a smaller time step can also be used. This is an area for future work.

**Continuity of Control Operation**

Continuity of the control operation follows the decision on the power flow analysis. In designing the control scheme, the decisions about how quick the control can respond and how it will operate have to be made. This has to be based on realistic situations. In this research, the developed control schemes operate continuously to tackle the voltage rise and line overload in real-time provided that the minute time step is thorough and fast enough to capture the variability of wind. Although an hour time step was applied in the beginning of this research, an hour is considered to be excessively large and that it is not possible to characterise the variability of voltage or line flow between hours. As will be presented in this thesis, a minute-by-minute time step is used.

**Generator Type**

Type of the generator has to be considered for the control scheme to locally manage the voltage rise and line overload. The ability to provide fast adjustment of active and reactive power is also significant for the developed scheme. As this research focuses on developing the control scheme that is able to capture and manage the variability effect of wind on voltage and line flow, a doubly fed induction generator is considered. For further application and extension, any generator types that are able to provide similar features can also be used.

**Thresholds to Identify Constraints**

A critical level, either for voltage or line flow, has to be defined in order to determine the instance when the control scheme is activated. Instead of monitoring the constraints against the statutory limits, a deadband is applied for the voltage and line flow levels such that the scheme is activated before the voltage or line flow reaches the limit. That is, when the constraints reach a threshold, the scheme reacts. With this setting, the statutory limits are expected to be maintained. The statutory limits for voltage and line flow are therefore not suitable to be used as the critical level as the constraints could become severe before the schemes take actions.

**Critical Generation Capacity**

In distribution networks, the DG capacity to be connected has been determined based on a 'fit & forget' approach where that available headroom for DG will not cause problems during N-1 contingency. Beyond the fit & forget capacity level, a critical capacity of the DG has to be predetermined before implementing the control scheme. According to the safe capacity level, then a 1-MW increase in the DG capacity is expected to cause the voltage and/or line power flow to breach the limits. Therefore, the critical generation capacity is used to test the operation and performance of the control scheme.

**Flexibility and Extendability of Scheme**

The control scheme initially developed in this research has been designed by taking into account its flexibility and extendability to be employed in a larger and more complex distribution network. The proposed scheme is decentralised and is based on relatively simple control methodologies with a number of control and setting options. These features allow the scheme to become flexible and extendable. In addition, the control scheme and case studies are developed in PSS/E interfaced Python which are widely-used within academia and industry. This also offers an opportunity for future development and implementation. The flexibility and extendability will provide an advantage for coordination or implementation with other smart grid-based technologies.

### 4.3.1 Overview of Decentralised Control Development

The following sections present a summary of a series of decentralised control methods for voltage management, thermal management and the management of both constraints. Development of these control methods has been progressive in that more and more sophisticated ideas have been implemented during the research programme. The order in which the schemes are presented in this chapter does not automatically correspond to the chronological order of the development.

To assist the reader to following the content of this (and later) chapter(s), Table 4 - 1, gives a summary of the voltage and thermal management developed in the research. They are presented with voltage management methods first, then thermal management methods and followed by voltage and thermal management schemes. An indication of the test systems with time resolution is also given.

**Table 4 - 1: Summary of decentralised, coordinated and centralised management schemes**

| **Chapters** | **Chapter 4** | | | **Chapter 5** | **Chapter 6** | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Forecast** | Perfect & persistence forecasting | | | Persistence forecasting | Persistence forecasting | | Perfect forecasting | | |
| **Active Management Spectrum** | Decentralised | | | Decentralised Operational Windows | Coordinated Tap-communications | | Centralised OPF-based V&T Mgt | | |
| **Schemes →<br>Studied Systems ↓** | V Mgt alone | T Mgt alone | V&T Mgt | V&T Mgt OW | V Mgt (alone) OW TAP | V&T Mgt OW TAP | Cost A equal share | Cost B favour WF 12 | Cost C favour WF 11 |
| 3 bus 11kV test feeder | | | | | | | | | |
| • Minutely - 1 hour (Scottish data) | ✓ | ✓ | ✓ | | | | | | |
| • Minutely - 1 hour (English data) | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ | | | |
| 12 bus 33kV rural DN | | | | | | | | | |
| • Minutely – 1 day (English data) | | | | | ✓ | ✓ | ✓ | ✓ | |
| • 10 minutely – 1 year (Scottish data) | | | ✓ | ✓ | | ✓ | | ✓ | ✓ |

### 4.3.2 Extension of Previous Work

In rural distribution networks, line resistance and reactance have similar magnitude. This means that the power factor control (or the reactive power control as expressed in this thesis) alone may be insufficient to mitigate voltage rise. With this in mind, this research has further extended the idea of AVPFC to include a generation curtailment mechanism aiming to improve the voltage control capability. In addition, the thermal capacity constraint is also handled in a way that both constraints are managed instantly and simultaneously, taking into account coordination and control priorities.

The proposed generator-based control scheme consists of two independent sub-schemes to perform voltage control and thermal overload management. The sub-schemes are based upon the regulation of active and reactive power of a DG unit and involve thresholds, target values, holding time and time delays. All of the voltage and thermal management schemes and simulation scenarios presented in this research are modelled and carried out in PSS/E interfaced Python and consider time series analysis in order to mimic real time functional behaviour. The control scheme modelling and power flow studies have been built using the PSS/E-Python interface platform developed in earlier work by O'Donnell [116], also conducted at the University of Edinburgh.

Besides MATLAB, PSS/E is a robust and widely-used power system simulation tool that can perform steady-state as well as contingency (dynamic) analyses [117]. In this aspect, a power flow study is performed in a different manner in that time-series raw data of the network, load and generation are input directly and the power flow solution is run without the need for detailed dynamic models and block diagrams. Control mechanisms of the developed schemes are scripted separately using Python and are promptly interfaced with PSS/E. Further explanations are presented in Appendix B. PSS/E software is relatively user-friendly and the Python interface offers flexibility in allowing an extension to the existing designed models where additional control schemes can be scripted separately but can be linked.

## 4.4 Decentralised Voltage Management Method

When connecting renewable DG units into distribution networks, DNOs normally request that the units are either able to operate at a fixed or within a specific range of power factor. In the UK, this is a power factor range of 0.95 inductive/capacitive (i.e., absorbing/producing reactive power), or a constant ratio of active and reactive power (e.g. fixed 0.95 or unity power factor), which modern wind turbines can comply with [38, 115]. From the DG owners' perspective, a unity power factor is generally desirable as it allows the DG unit to generate at its maximum power output yielding the highest energy export. The operating power factor requirement also aims to maintain voltage profiles at the connection point and surrounding busbars within specified voltage statutory limits and minimises any possible interference with the existing voltage regulation performed by OLTC transformers or line drop compensators. According to the ESQCR [118], the statutory voltage limits for 33kV and 11kV are ±6% of the nominal value (±1.06pu). In this research, this voltage statutory range is used throughout.

The proposed voltage scheme adopts the basic premise of the earlier [15, 16, 78] voltage control scheme by utilising the reactive power control capability of a DG unit and is further developed to include the regulation of active power (i.e. generation curtailment of the DG unit) in order to improve the voltage management capability. Upon development of the proposed V Mgt scheme, it is assumed that DNOs allow a more flexible policy in terms of voltage control performed by DG units. Here, the generation curtailment is applied only as a back-up scheme when the reactive power control is not successful (i.e. the reactive power capability is reached while the voltage still exceeds the limit). The main reason for this is to allow the maximum possible capacity of DG connection and to minimise the amount of power loss in the curtailment process. Detailed control mechanisms and the combined operation of the reactive power control and the active power curtailment are identified in the next subsection. Although the proposed scheme applies to any type of generation, wind power will be considered in this research.

The control scheme operates on a discrete time basis with conditions in one period used to define control actions in the next. It manages voltage constraint by way of a series of *threshold* and *target* values which dictate whether the control actions are required at any given time step. Threshold values are defined at a level within the voltage limits. When measured values exceed these, corrective action is taken to reduce values to a target value at a more conservative level below the threshold. The deadband created by these two values avoids unnecessary activation of the control mechanisms. The correction is based on two methods: (i) reactive power control using real-time sensitivity analysis or step-wise power factor method to define reactive power set point and (ii) generation curtailment using reduction rate method or real-time sensitivity analysis to define active power set point.

Where corrective action has been taken, operation will continue to be monitored against the thresholds to determine whether normal wind farm operation can be allowed without violating constraints. Both the threshold and the target values are particularly useful in the context of variable generation where fluctuations over a short period of time are frequent. The time step, threshold and target values can be set in such a way to promote more or less conservative operation. The settings for the threshold and target values are explained in more detail in Section 4.6.

### 4.4.1 Reactive Power Control

Reactive power control (or dual mode control) is developed from the idea of combining the advantages of two operation modes of a generator: constant power factor control (PFC); and voltage control (VC). The scheme enables the DG unit to use its ability to operate at different power factor within the reactive power capability range. Such capability is dependent upon the type and size (active power output) of the DG unit and the operating requirements of the DNOs. For instance, a 1-MW generator with a 0.95 power factor capability requirement is able to provide approximately 0.33-MVar inductive/capacitive reactive power support according to:

$$Q_{Inductive}, Q_{Capacitive} = \frac{P}{power\ factor} \times \sqrt{1 - power\ factor^2} \qquad (4 - 1)$$

For a DFIG wind turbine, in this research, it is assumed that the reactive power capability is within the blue area as shown in Figure 4 - 4. Alternative formulations of capability are examined in Chapter 6.

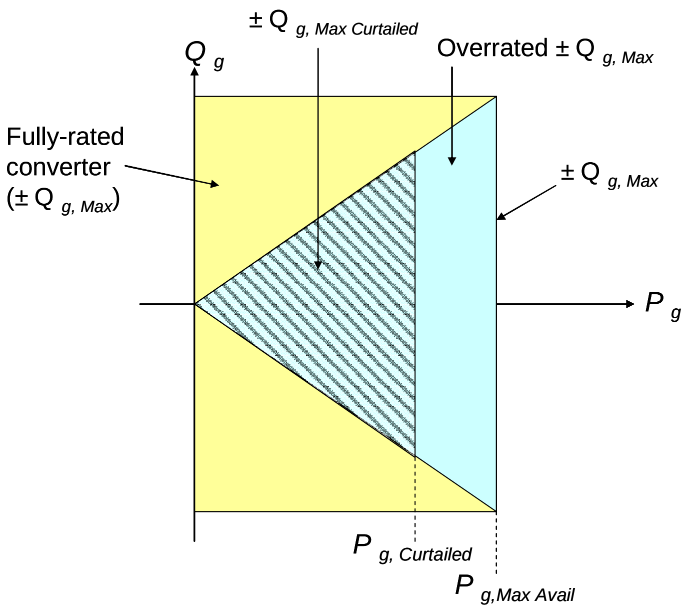
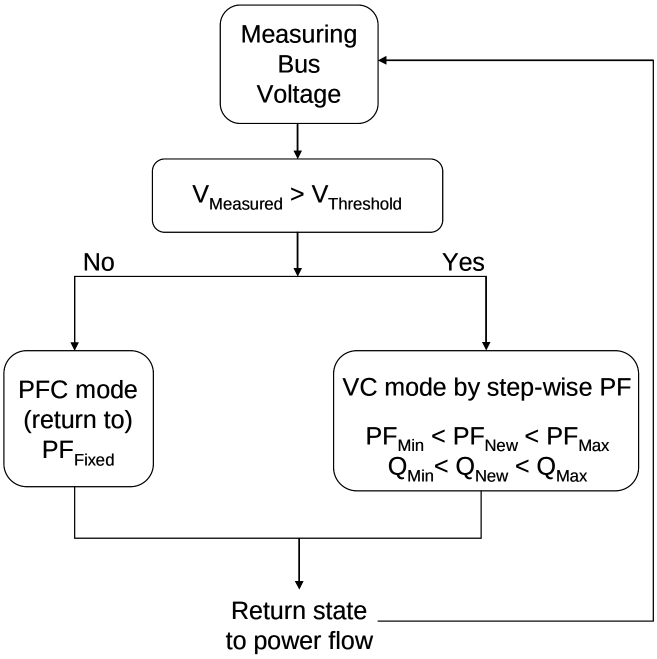
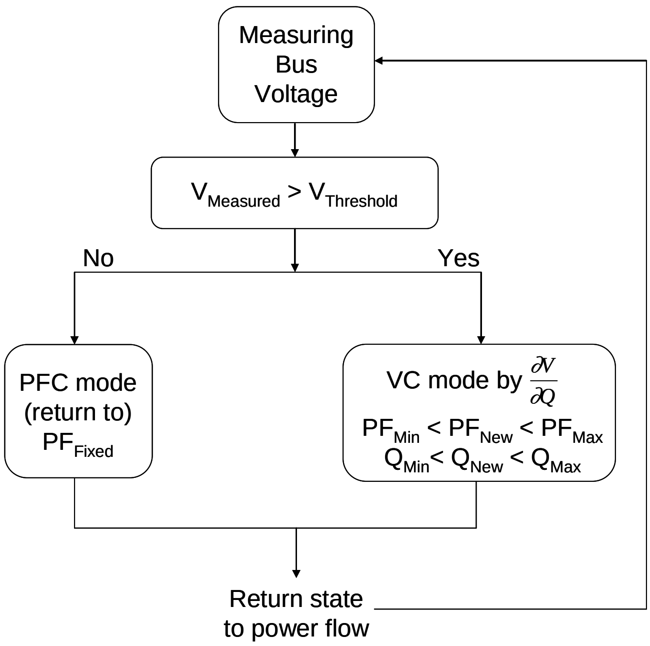



**Figure 4 - 4: Active-reactive power characteristic**

A functional diagram of the reactive power control is shown in Figure 4 - 5. The notations $PF_{Min}$, $PF_{New}$ and $PF_{Max}$ define the maximum, new (next period) power factor and minimum power factor values, respectively, in which these values specify the minimum ($Q_{Min}$), new required ($Q_{New}$) and maximum reactive power ($Q_{Max}$) values. Voltage at the point of DG connection is measured in real-time against a pre-defined threshold ($V_{Threshold}$) that is set below the upper voltage statutory limit depending on the network conditions and demand and generation characteristics. During normal operation when the voltage is within limits, i.e. below $V_{Threshold}$ and no previous control action is applied, the constant power factor control mode maintains the power factor at a fixed predefined value.




(a)



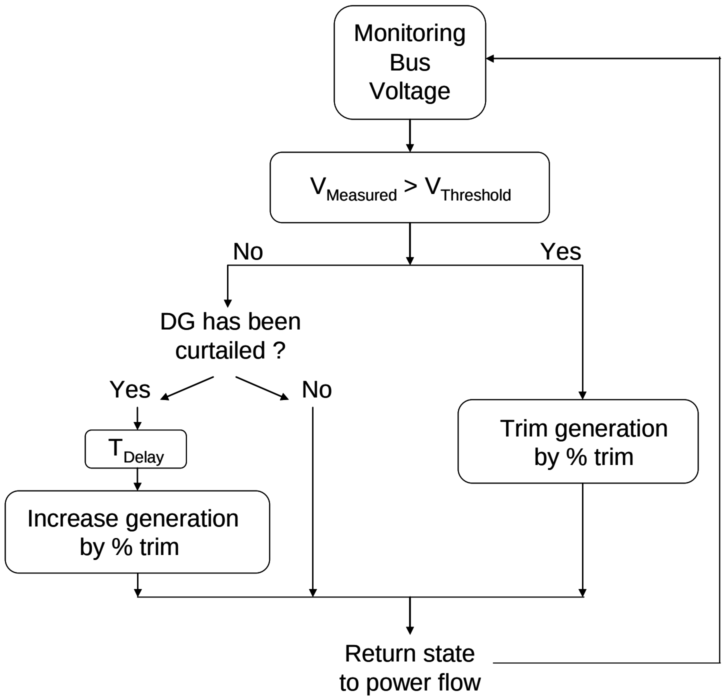

(b)

**Figure 4 - 5: Functional diagram of the reactive power control (dual mode control) based on (a) step-wise power factor and (b) sensitivity analysis**

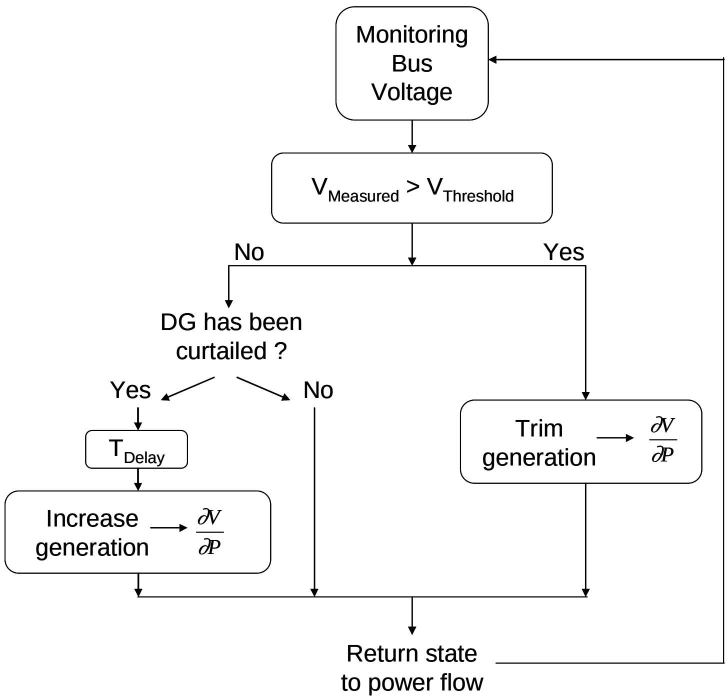
In case the voltage at the connection point rises above $V_{Threshold}$, the voltage control mode is adopted to provide reactive power compensation that brings the voltage within the statutory limit. In this process, the generator will adjust its power factor set point to become more inductive. Two methods of adjusting power factor are developed: (i) step-wise power factor and (ii) voltage sensitivity analysis ($\partial V/\partial Q$). In the first method, as depicted in Figure 4 - 5 (a), the new power factor (reactive power) is defined as a step from unity up to the power factor capability or requirement of DG. In the second method (Figure 4 - 5 (b)), the new power factor set point is calculated using a real-time voltage/reactive power sensitivity analysis. The $\partial V/\partial Q$ sensitivity computes the amount of reactive power required to keep the voltage within a specified voltage target ($V_{Target}$) that is set below $V_{Threshold}$. The voltage sensitivity analysis relates to the calculations of voltage deviation ($\partial V$) to a nominal 1-Mvar ($\partial Q$) decrease of the generator. The reactive power control using both methods was initially developed based on the perfect forecasting assumption. Later, the sensitivity analysis was revised to consider the real situation with persistence forecasting.

### 4.4.2 Active Power Curtailment

The regulation of active power for voltage constraint management is concerned with trimming an amount of power but is only adopted as the last resort when the reactive power control is not successful. This control function is required when the reactive power set point reaches the DG's reactive power capability range while not being able to keep the voltage below the voltage threshold. The worse case could be a scenario when high generation coincides with low demand over a certain period. The functional diagram of the generation curtailment scheme is shown in Figure 4 - 6.




(a)




(b)

**Figure 4 - 6: Functional diagram of the generation curtailment for voltage control based on (a) reduction rate and (b) sensitivity analysis**

When the reactive power capability is reached but voltage rise remains, active power curtailment is activated and the DG unit trims its power output. After being curtailed and after the voltage rise problem is solved, a time delay ($T_{Delay}$) is enforced to maintain the safe operating condition before allowing the DG unit to increase its output back to the previous level. This has an advantage of ensuring the variability of DG output (wind) will not worsen the voltage in the next time step. This also reduces the frequency of changing active power of the DG, i.e., no curtailment required during the time delay.

Two methods are used in determining how much the generator is required to trim its output: (i) active power reduction rate or generation curtailment rate (% trim) with enforced time delay; and (ii) voltage sensitivity analysis ($\partial V/\partial P$). Both methods are similar in terms of control to provide real-time voltage management however the difference is the determination of the trimmed amount required for the control process. The first method, shown in Figure 4 - 6 (a), defines the amount for curtailment at a constant rate whereas the sensitivity method (Figure 4 - 6 (b)) calculates the sensitivity of voltage change due to a reduction in active power to estimate the curtailed amount. Similar to that in the reactive power control, the voltage sensitivity analysis relates to the calculation of voltage deviation ($\partial V$) to a nominal 1-MW ($\partial P$) decrease of the generator. Detailed control is presented in the next section. After the curtailment, the voltage rise problem is expected to be overcome. The new operating conditions (i.e. the new power factor and the new power output set point) for the DG unit are held until the next cycle of measurements (or the next time step). Should the voltage exceed the threshold, the DG output is further curtailed in the next cycle and the control process repeats. Generation curtailment offers comparable advantages and disadvantages based on the control performance, net power export and scheme feasibility.

The active power curtailment using the reduction rate was again developed initially based on the perfect forecasting assumption. Then, during the time of developing the reactive power control using the sensitivity method with the persistence forecasting assumption, the same consideration was also implemented in the active power curtailment.

### 4.4.3 Full Voltage Constraint Management

As explained earlier, the voltage management scheme uses reactive power control and active power curtailment to perform voltage rise mitigation action. For each method, different techniques have also been developed. In this section, control mechanisms of the combined reactive power control and active power curtailment scheme for the voltage rise management are presented. This was the first attempt towards extending the previous work (presented in Section 4.2). Validations of the voltage management scheme are presented later.

#### 4.4.3.1 Voltage Management based on Reduction Rate

The voltage management scheme combines the reactive power control based on t the step-wise method and the active power curtailment based on the % trim enforced $T_{Delay}$, both developed based on the perfect forecasting assumption. When voltage rise occurs, the reactive power control using the step-wise method adjusts the power factor of a generator by step from normal operation, i.e., unity power factor, to become 0.01 step more inductive within the power factor capability, i.e., 0.95,. The active power control adopting the % trim enforced $T_{Delay}$ method applies a basic idea where the amount of power required for trimming in each cycle is a constant proportion of the output at that instant. For instance, a generation curtailment rate of 10% means the power output of a DG unit is reduced by 10% of the actual power output at that instant, i.e., it reduces unused power output, minimising loss of energy. The ramp rate of the DG unit is also considered.

The necessary generation reduction rates may vary for different DG units at different locations. Decisions on choosing the values are based on the sensitivity of the network voltages to the variations in demand and generation patterns. The analyses for different reduction rates, time delays and the subsequent considerations for choosing appropriate values are presented and discussed in Section 4.10.

#### 4.4.3.2 Voltage Management based on Sensitivity Analysis

The voltage management scheme combining the reactive power control and the active power curtailment based on the voltage sensitivity method is explained in this subsection. The sensitivity analysis utilises real-time monitoring and calculation of the amount of active and reactive power required to provide corrective voltage mitigation actions. The required active power to be trimmed or reactive power to be absorbed (i.e. the DG unit is being inductive) is estimated using the difference between the target voltage ($V_{Target}$) and the measured value ($V_{Measured}$). In each period the local state of the network is used to obtain $\partial V$ to unit changes in generator reactive or active power output: $\partial V/\partial Q$ or $\partial V/\partial P$. The sensitivity values are calculated for every time step as the voltage changes with variations in demand and generation.

The reactive power ($\partial Q$) absorbed to alleviate voltage rise is computed from the target and measured voltages and the sensitivity value as in the following:

$$\Delta Q = \frac{V_{Measured} - V_{Target}}{\frac{\partial V}{\partial Q}} \tag{4 - 2}$$

and the active power to be curtailed ($\partial P$) is:

$$\Delta P = \frac{V_{Measured} - V_{Target}}{\frac{\partial V}{\partial P}} \tag{4 - 3}$$

The actual active or reactive power of the DG unit to be applied will be limited by the capabilities of the generator, that is, its reactive power range and ramp rates. As the voltage progressively returns to normal operation, $\partial P$ and $\partial Q$ values will become negative as the set points are revised upwards.

Once adjustments are made for the current period $t$, active and reactive power set points for the next period $t+1$ are obtained. This process is rather simple and straightforward for the case of having wind and demand forecast available (perfect forecasting), i.e., $\partial P$ and $\partial Q$ values are applied to the forecasted active and reactive power output at $t+1$. On the other hand, in the absence of wind and demand forecasts at the site, the calculation assumes that the wind output $W \in [0,1]$ and demand in $t+1$ will be the same as in $t$ (i.e. persistence forecasting, $W_t = W_{t+1}$). This means the targets are unlikely to be precisely achieved. However, with short-time steps, the scope for substantial changes in conditions is reduced, although this is an area of further work.

For the persistence forecasting assumption, the active power output set point at $t+1$, $SP_{t+1}$, defines the wind farm's maximum allowed production:

$$SP_{t+1} = \frac{P_t - \Delta P}{W_t \times P_{nom}} \tag{4 - 4}$$

where $P_t$ is the active power output and $P_{nom}$ the nominal wind farm capacity. The power factor set point $PF_{t+1}$ is given by:

$$PF_{t+1} = \frac{P_t}{\sqrt{P_t^2 + (Q_t - \Delta Q)^2}} \tag{4 - 5}$$

where $Q_t$ is the reactive power output at $t$.

The sensitivity analysis ($\partial V/\partial Q$ and $\partial V/\partial P$) is significant as it is the first step towards the corrective action particularly the voltage-reactive power sensitivity used as the main tool to perform the voltage management. The calculation of the sensitivities requires knowledge of the network parameters in the vicinity of the wind farm. In the simulation this is achieved by conducting a separate power flow for conditions in each period. For real implementation, as wide-area monitoring is excluded from this local approach, alternatives are required. The knowledge of local network parameters can be estimated, for instance, by adopting an equivalent circuit of the network or having a localised state estimator. The latter would involve a real-time computer analysis of the network using only the available local measurements.

#### 4.4.3.3 Operation of Voltage Constraint Management

The separate control mechanisms of the reactive power control and generation curtailment are explained in the previous subsections. In order to implement the voltage management scheme by combining both approaches, coordinated operation is required.

Figure 4 - 7 depicts the high-level control philosophy of the V Mgt scheme embedding reactive power control and generation curtailment. The V Mgt scheme uses the reactive power control as the primary tool to manage the voltage constraint and is assisted by the active power curtailment. The overall control philosophy can be separated into two parts: ‘constraining actions’ and ‘return to normal operation’.

Voltage at the DG connection point (i.e. wind farm connection point) is monitored continuously against a voltage threshold, $V_{Threshold}$. During normal operation where with voltages within limits and no previous control actions (i.e. power output set point is 1pu), the DG unit operates at normal (unity) power factor and the mechanism returns to monitoring stage (step 1). If voltage rise occurs, the control algorithm falls into the constraining actions part where first of all the reactive power capability of the generator is used in a way to overcome the constraint, i.e., the power factor is adjusted to become more inductive to lower the voltage to the voltage target, $V_{Target}$. The new power factor set point is calculated based on the real-time sensitivity method, $\partial V/\partial Q$ (used only for the reactive power control), to define the reactive power required to reduce voltage to $V_{Target}$. The mechanism then returns to step 1. If the required reactive power exceeds the DG reactive power capability, its active power output is curtailed, using either of the outlined two options. The calculation accounts for the DG (wind) power available at the current wind speed $P_{avail}$ (as defined by the wind anemometry and power curve) as well as the wind farm’s ramp rate limits.

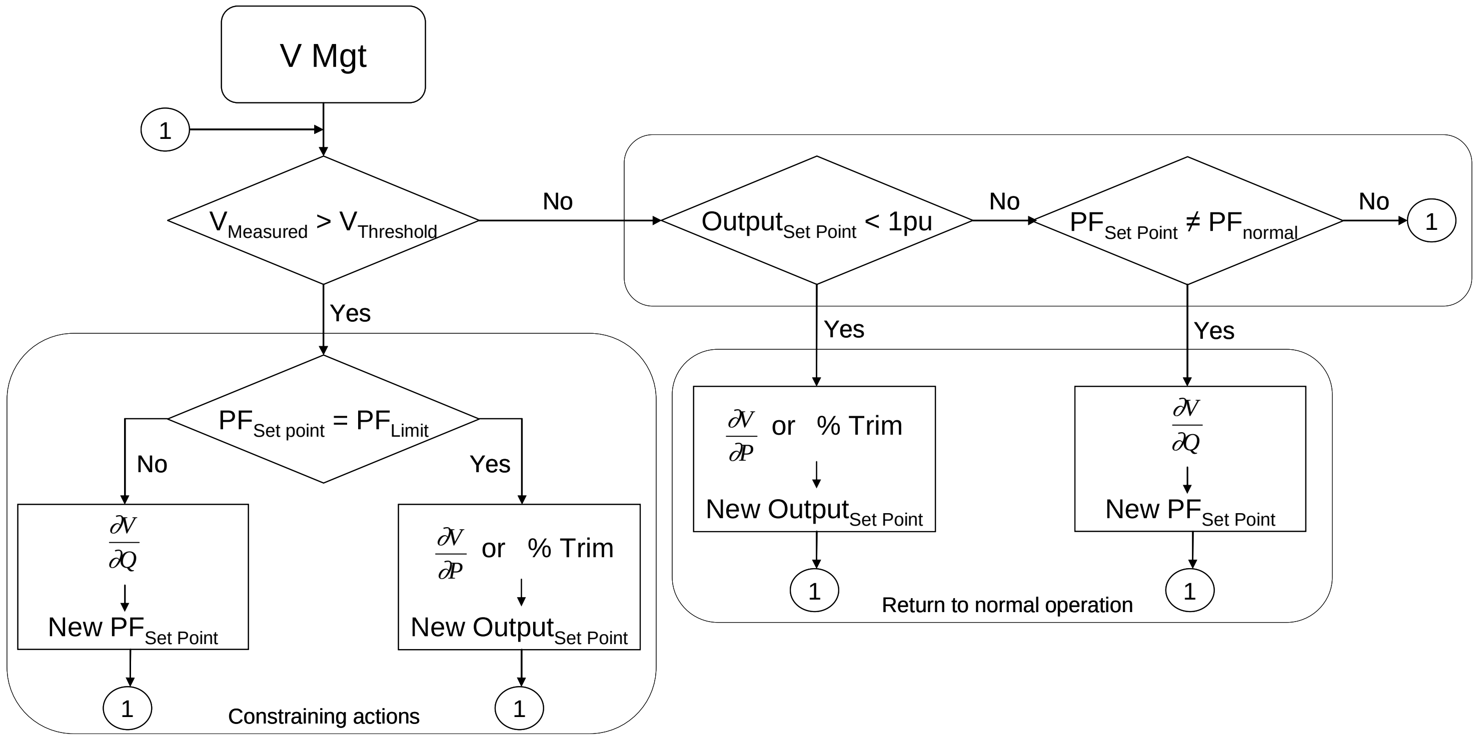



**Figure 4 - 7: High-level voltage constraint management scheme**

In case voltage falls below $V_{Threshold}$ but control actions have already been taken previously (i.e. power factor and/or power output set points are different from nominal/normal operation), then it is possible for it to return to initial settings (progressively if necessary) and make the most of the available wind. Here, the reverse process is used to bring the set points back to normal values. The decision to adjust the active or reactive set points depends on whether the turbine's active power outputs are either (i) unconstrained, or (ii) constrained below the available wind power, $P_{avail}$. In case (i), reactive power import is reduced and a new, less inductive, set point is calculated. In case (ii), a new, higher, active power set point is defined. In all cases, if using the reduction rate for active power curtailment the same constant reduction rate is reversely applied, and if the sensitivity method is used the relevant sensitivity is calculated, in accordance with turbine ramp rate limits and the available production capability. This moves the wind farm towards normal unconstrained operation.

While intended to manage voltage rise, the algorithm could be modified to facilitate voltage support during low voltage episodes to comply with statutory low voltage limits or to reduce losses. With wind turbines this would be restricted to the export of reactive power as wind production cannot be raised beyond the available wind power, $P_{avail}$.

## 4.5 Decentralised Thermal Constraint Management

The thermal constraint management was developed alongside the decentralised voltage management scheme to extend the control capability for managing multi-constraint situations. It uses active power curtailment as a tool to perform line overload mitigation action. In this research, the term ‘thermal’ is used to refer to line thermal overload and is synonymous to maximum line power flows. Different techniques have been developed and are presented in this section.

The regulation of active power in thermal constraint management is concerned with trimming power to ensure the maximum line capacity is not exceeded. The determination of the amount of power required in the curtailment process is crucial for the thermal management scheme as it provides immediate and preventive actions to manage the thermal constraint. Three methods for determining the required trim amount are proposed: (i) thermal reduction rate enforced time delay (% trim); (ii) thermal set point; and (iii) thermal sensitivity analysis ($\partial S/\partial P$). Validations of the thermal management methods are presented later. The control mechanism of each method is outlined in the following subsections.

### 4.5.1 Thermal Management based on Reduction Rate

A functional diagram of the proposed thermal management scheme (T Mgt) based on thermal reduction rate and thermal set point is shown in Figure 4 - 8. The thermal reduction rate enforced time delay method follows similar processes to the generation curtailment rate presented in the V Mgt scheme. The scheme begins by continuously monitoring the line loading, in this case the one immediately transferring power from the DG connection point, against a given line capacity threshold. If the threshold is breached, the DG output is trimmed. The amount of power required to be curtailed is a constant pre-specified proportion of the DG power output (e.g. curtailment by 10% of power output in each measurement cycle or time step). The control algorithm also takes account of the DG ramp rate limitation. After the curtailment, if the line capacity is successfully maintained below the threshold, the time delay is counted before the DG unit is allowed to increase its output at the same curtailment rate back to the normal operation.

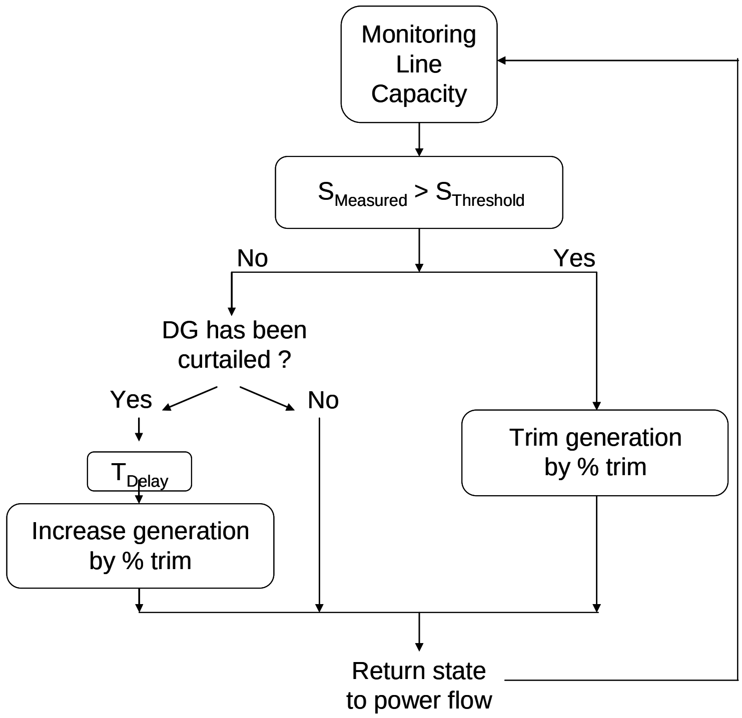



**Figure 4 - 8: Thermal constraint management using thermal curtailment rate**

### 4.5.2 Thermal Management based on Output Set Point

A functional diagram of the active power curtailment using thermal set point method is shown in Figure 4 - 9. The scheme is based on the Active Power Flow Management (APFM) developed by Currie *et al.* [12, 75]. In this context, the APFM method is simplified to adopt the threshold and target values ($S_{Threshold}$ and $S_{Target}$). The power output of the DG unit is reduced when the instantaneous circuit loading exceeds the pre-defined $S_{Threshold}$. The amount required to be trimmed is calculated based on the needs of the loads and other generators in the vicinity of the DG unit. For instance, as shown in Figure 4 - 10, those participants connected to bus 3 (load and *DG1*) will need to be included in the determination of the safe output level of *DG2* according to Equation 4-6:

$$DG2_{Output\ Safe} + Load + Losses + DG1 \leq Cap_{Intact} \qquad (4\text{ - }6)$$

where $Cap_{Intact}$ is the actual capacity of circuit where the DG unit is connected, and *DG1* is generation capacity from other generators in the vicinity of *DG2*.

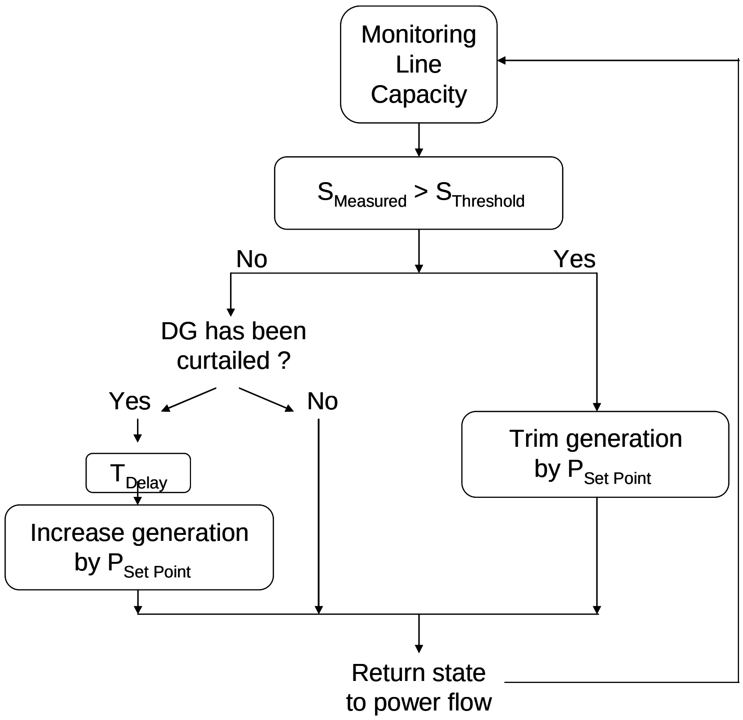



**Figure 4 - 9: Thermal constraint management using output set point**

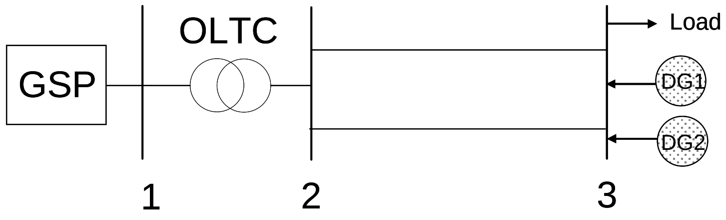



**Figure 4 - 10: A 3-bus test feeder**

The estimated safe output level (*$DG2_{Output\ Safe}$*) determines the total MW required to be trimmed based on the ramp rate of the DG unit where load, losses and generation (*DG1*) values can be estimated based on historic data. Again, after the curtailment if the line capacity is successfully maintained below the threshold, the time delay is enforced before the DG unit is allowed to increase its output at the same curtailed amount (if less than ramp rate) back to the normal operation.

### 4.5.3 Thermal Management based on Sensitivity Analysis

The control philosophy of the proposed T Mgt scheme using the thermal sensitivity method is illustrated in Figure 4 - 11. The mechanism is similar to the active power curtailment with voltage sensitivity in the V Mgt scheme. The scheme monitors the line flows against the line threshold ($S_{Threshold}$). If the measured line loading ($S_{Measured}$) exceeds $S_{Threshold}$, the scheme will start the constraining actions by estimating the amount of power required to be curtailed and issue the new output set point (i.e. given the nominal output set point of 1pu, the new set point will become less than 1pu). The ramp rate of the DG unit is also used in the estimation. After the curtailment, the control process restarts (i.e. returning to step 1 where the line capacity is monitored). If the line capacity is managed to be below the threshold and the output set point is less than 1pu (i.e. the DG has been curtailed and is producing power at the safe output level), the sensitivity estimation is applied to return to normal operation.

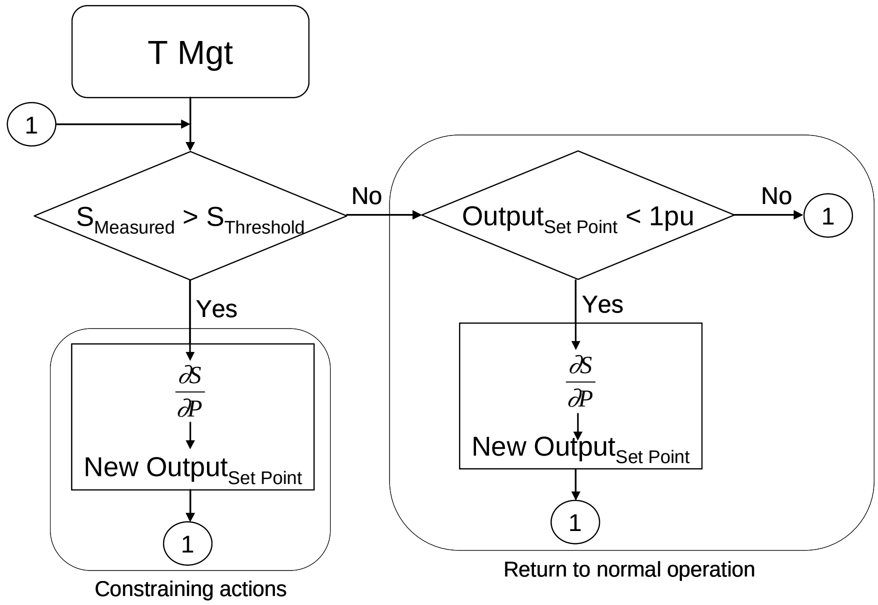



**Figure 4 - 11: Thermal constraint management using a thermal sensitivity method**

The method was originally developed based on the assumption where the DG (wind) resource and demand forecast is absent (persistence forecasting). The amount of power to be curtailed in order to maintain the line loading within a given line capacity target is estimated using the sensitivity of the binding line capacity to the power output of the DG unit ($\partial S/\partial P$). The thermal sensitivity is determined by the line loading deviation $\partial S$ to a nominal 1-MW decrease of the generator. Then, the required power to be curtailed is computed using the difference between the line capacity target and the measured value (taking into account the ramp rate limitation of the generator) according to:

$$\Delta P = \frac{S_{Measured} - S_{Target}}{\frac{\partial S}{\partial P}} \tag{4 - 7}$$

The active power set point for the next period t+1 ($SP_{t+1}$) is determined using Equation (4 - 4).

## 4.6 Defining Settings of Decentralised (Voltage and Thermal) Management Schemes

The threshold values ($V_{Threshold}$ and $S_{Threshold}$) are used to determine whether the control mechanisms are required in response to the constraints. Here, the threshold values are set below the maximum voltage statutory limit (1.06pu) or the maximum line capacity (100%). If voltage or power flow exceeds the corresponding threshold, corrective action is taken. On the other hand, the target values ($V_{Target}$ and $S_{Target}$) are used as a safe level and are set below the thresholds to estimate the active or reactive power set point required by the corresponding control scheme. Then the DG unit operates with the set point values (i.e. power factor and/or power output) such that secure operation is maintained. The operation will be continuously monitored against the corresponding thresholds to determine whether normal operation of the DG unit can be allowed without violating the constraints. Once the DG unit is in its normal operating condition, the control process repeats.

Adopting the threshold and the target values are particularly useful in the context of variable generation such as wind because of its frequent fluctuations over a short period of time. The use of the binding threshold and target values can help to avoid unnecessary activation of the control mechanism due to negligible voltage rise or line overload that would otherwise occur if only one single setting is used (i.e. a single setting of 1.05pu will activate the corresponding control mechanism if the monitored parameter is just 1.051pu). In the case of constant generation (e.g. gas or diesel unit), the proposed threshold value equals the target value. This is possible as the more modest power output fluctuations allow more precise control mechanisms.

In the reduction rate method, the time delay is applied before the generator is allowed to increase its output by one step back to the previous level after the constraints have been cleared out. This mechanism will ensure the constraints are kept within the limit to avoid a *hunting effect* that can arise from a continuous fluctuation of the DG output due to a short-time variability of resource and the interference with other existing network control devices. In addition, the use of time delay will allow those devices to actuate where necessary.

## 4.7 Joint Voltage and Thermal Management

The detailed control algorithms of the voltage control and thermal overload management schemes as explained in the previous sections separate the management actions based on the individual constraints so that each constraint can be solved independently. However, when voltage and line capacity concurrently exceed the thresholds, the activation of independent voltage and thermal management schemes may result in a local *hunting effect*, where the interface of the schemes attempts to manage the voltage and thermal problems at the same time. Such circumstances require a strategy to prioritise the individual schemes to gain the most effective control in a coordinated manner. In this section, coordination and priority of the individual schemes are introduced.

For active management to provide real-time corrective actions of multiple simultaneously occurring constraints, particularly when involving the regulation of active and reactive power of the DG unit, it is vital to coordinate each control schemes such that control actions are not unnecessarily replicated. Defining a priority control can provide appropriate sequences of actions to manage constraints effectively. The control priority also ‘locks in’ the use of one scheme at a time to avoid issues such as local *hunting* that may arise from simultaneous functioning.

Under normal conditions, where no control mechanism is active, the DG unit will operate at its normal, fixed power factor and produce power as dictated by the available primary source. If either the voltage or thermal threshold is breached, the corresponding constraint management mechanism is activated. In a severe situation when both constraints appear simultaneously, a control priority will be given to the thermal management scheme. This is key to the scheme’s operation as reactive power imports for voltage management (if being activated) may increase the complex power flow and could worsen the line overload. While generation curtailment for thermal constraint management will also tend to limit voltage rise it may not be adequate in severe situations. Therefore once the line overload is handled, voltage management will activate for further action as necessary. In the case where active power curtailment is needed for thermal constraint management and voltage rise still occurs, further power output trimming will follow to ensure both constraints are completely satisfied. Modifying DG active and reactive power will both affect line apparent power flow. The priority given to thermal constraint management means that DG reactive power flows are assumed unchanged. This means that use of active power changes alone avoids large inaccuracies but errors from persistence forecasts of demand will be present.

The summary of the control priority is shown in Table 4 - 2. The probability of constraint occurrences can be defined by 4 situations: normal, voltage rise only, line overload only and simultaneous voltage rise and line overload. For a single constraint, either the voltage or thermal management takes action. The control priority is used when both constraints occur at the same time. Case study and performance assessment of the joint voltage and thermal management are presented later. In the next section, validation of the individual schemes will be presented.

**Table 4 - 2: Control priority for the V&T Mgt full approach**

| Voltage rise | Line thermal overload | Command |
|---|---|---|
| No | No | No action |
| Yes | No | V Mgt |
| No | Yes | T Mgt |
| Yes | Yes | T Mgt then V Mgt (if necessary) |

## 4.8 Validation of Individual Schemes

First stage of validation aims to show individual components of voltage and thermal management schemes, in other words, testing only reactive power control or active power curtailment. The reason for that is that the full scheme (joint voltage and thermal management) combines the effect of both constraining actions and it is more difficult to discern the contribution of each part.

In this section, control mechanisms of individual voltage management and thermal management are demonstrated. A simplified pattern of wind is used to clarify the operation and perfect forecast of demand and wind generation is used to simplify the methods. The corresponding control settings for the individual voltage and thermal management schemes are summarised in Table 4 - 3.

**Table 4 - 3: Summary of the V&T Mgt control settings requirement**

| Schemes | V-Mgt | | T-Mgt |
|---|---|---|---|
| Methods | Reactive power control | Active power curtailment | Active power curtailment |
| Reduction Rate | • Step-wise PF<br>• Q capability<br>• V threshold<br>• V target | • % trim<br>• V threshold<br>• Time delay | • % trim<br>• S threshold<br>• Time delay |
| Sensitivity Analysis | • $\partial V/\partial Q$<br>• Q capability<br>• V threshold<br>• V target | • $\partial V/\partial P$<br>• V threshold<br>• V target | • $\partial S/\partial P$<br>• S threshold<br>• S target |

### 4.8.1 Reactive Power Control based on Sensitivity Analysis and Step-Wise Power Factor for Voltage Management

In this subsection, firstly, the reactive power control based on the sensitivity analysis is demonstrated. Then, under the same test system, load and generation condition, the step-wise power factor method is tested.

The first scheme developed in this research was the reactive power control for voltage management using the sensitivity analysis approach and with perfect forecasting. The validation was carried out in a 3-bus test feeder depicted in Figure 4 - 12. Peak demand at bus 3 is 2.2-MW. A combined heat and power (CHP) unit and a wind farm are also accommodated at the end of the feeder. The wind and demand profiles applied in the test are shown in Figure 4 - 13. The one-hour profiles were obtained for central Scotland on 14$^{th}$ August 2003 where the wind speed data was produced using a generic wind power curve [119]. The chosen period was in the summer where the demand was relatively low but with high wind speeds. The CHP unit operates at constant power output of 4-MW with 0.98 capacitive power factor. A 'fit and forget' approach (i.e., the maximum capacity that can be connected without causing voltage rise or line overload problems) for the wind farm would lead to a maximum of 5-MW of capacity. A 6-MW wind farm is used in the validation in order to reveal mechanisms of the reactive power control. The wind farm operates at unity power factor but has reactive power factor capabilities of 0.95 inductive/capacitive. The 3-bus system is tested on a minute time step over a 60-minute time period under worst case (maximum generation and minimum demand). Voltages at 33kV and 11kV are required by statute to be within ±6% of nominal. The deadband for $V_{Target}$ was set to 0.25% below the upper voltage limit (i.e., 1.0575pu) and $V_{Threshold}$ was 1.06pu. For the wind farm producing at 6-MW, the maximum reactive power capability is ±1.97-Mvar (using Equation (4 - 1)).

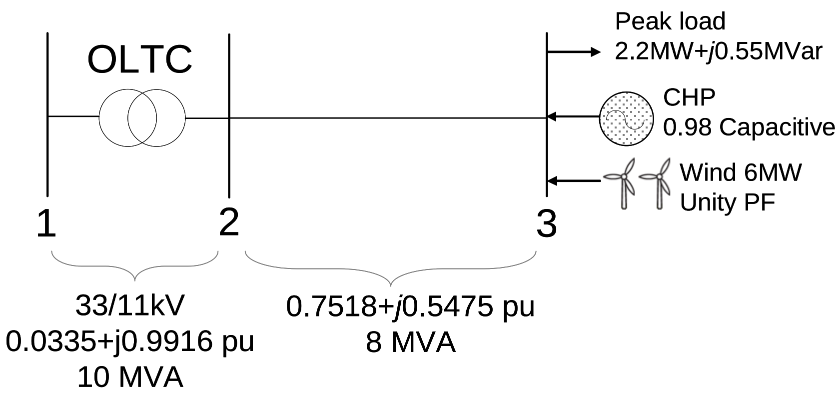



**Figure 4 - 12: Single line diagram of a 33/11-kV 3-bus test feeder (100-MVA base)**

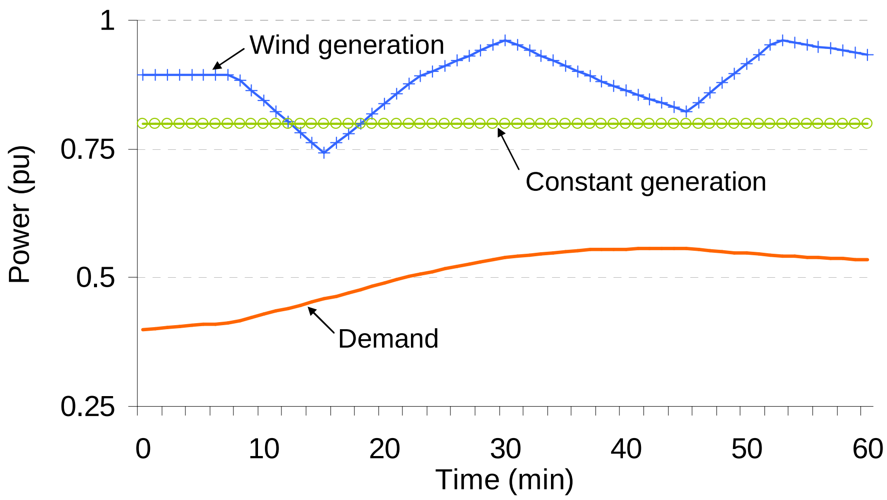



**Figure 4 - 13: 60-minute time series for demand and generation profiles**

The voltage profiles at bus 3 for no control, the control based on the sensitivity analysis and the step-wise power factor are shown in Figure 4 - 14 (top). At normal fixed power factor (no control), the system voltage at the DG bus when the wind farm is producing 6-MW power output already breaches the upper voltage limit, as seen at the beginning of the measurement, between minutes 20$^{th}$ to 40$^{th}$ and after minute 48$^{th}$ due a large amount of power being produced at low demand.

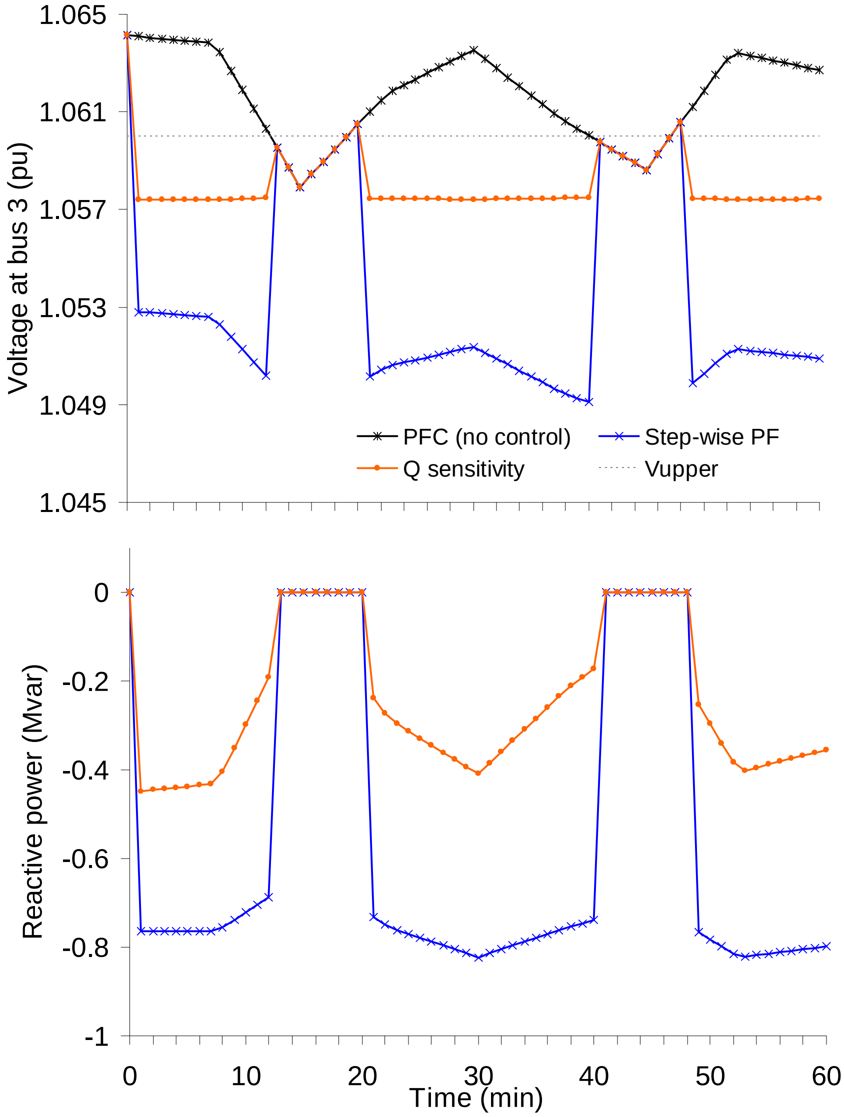



**Figure 4 - 14: (Top) voltage profile at bus 3 and (bottom) reactive power output for reactive power control based on the step-wise power factor and the (Q) sensitivity method**

Voltage control performed by the sensitivity analysis approach reveals that during voltage rise (the first 12 minutes, between minutes $20^{th}$ to $40^{th}$ and after minute $48^{th}$), it is able to bring the voltage down effectively (given that the reactive power control action of wind turbine is relatively fast, i.e., within seconds, the action is seen at minute 1). This is a result of the sensitivity analysis (with knowing the information of wind and demand for the next period) that estimates the corresponding amount of reactive power absorption (Figure 4 - 14 (bottom)) based on $V_{target}$. Where voltage at the DG bus drops below the voltage upper limit, a normal operating mode is applied (i.e., fixed unity power factor).

For the step-wise power factor method, the power factor capability is assumed to be 0.95 inductive/capacitive with a step of 0.01, i.e., the allowable set of power factor consists of unity, 0.99, 0.98, 0.97, 0.96 and 0.95 power factor, in order to overcome the voltage problem. As shown in Figure 4 - 14, the reactive power control based on the step-wise power factor is also able to overcome the voltage rise problems over the periods. In comparison with the sensitivity analysis-based voltage management however the step-wise method reacts with greater amount of the reactive power absorbed (Figure 4 - 14 (bottom)) due to the step adjustment of the power factor, i.e., from unity to 0.99 inductive. In this situation, the voltage rise problem only requires one step power factor adjustment. However, this method is not as effective as the sensitivity analysis-based solution in terms of accuracy and smoothness in maintaining the voltage at $V_{target}$. In addition, such a large step change in voltage may cause voltage problem at nearby location and may not be allowed. The step-wise power factor method was only investigated during the beginning of this research as an alternative method whereas the sensitivity analysis-based approach is considered for further extension. The sensitivity analysis method considering more realistic situation (i.e., in the absence of forecast of wind and demand) is demonstrated later.

### 4.8.2 Generation Curtailment based on Reduction Rate for Voltage Management

In this subsection, the control mechanism of the generation curtailment for voltage management is presented. The generation curtailment scheme is based on the reduction rate (% trim) considering the wind unit's ramp-up rate and the time delay ($T_{Delay}$) is fixed to 5 minutes. In the analysis, four reduction rates are examined: 5, 10, 15 and 20% of the rated capacity.

The tests were carried out under the same 3-bus feeder, load and generation situation as in the previous validation. The generation curtailment at four increment reduction rates is applied and the control actions are depicted in Figure 4 - 15. To clearly illustrate the mechanism in each cycle of the curtailment function, the 5-minute time delay was also applied prior to the action after the constraint is detected, i.e., the generation curtailment scheme responds at minute 5 following the time delay specified. After the time delay is up, the first attempt to reduce voltage is taken. As seen, the 5% and 10% rates are not able to mitigate the voltage rise immediately compared to the 15% and 20% rates. After the curtailment has taken place, the time delay is applied to ensure no sudden voltage variation occurs due to variability and to minimise the adjustment of the turbine. After the time delay is up, the wind farm is allowed to increase its power output back at the same rate. In terms of smoothness of voltage response, the 5% rate performs the finest control action whereas the 20% rate causes a large voltage step down/up.

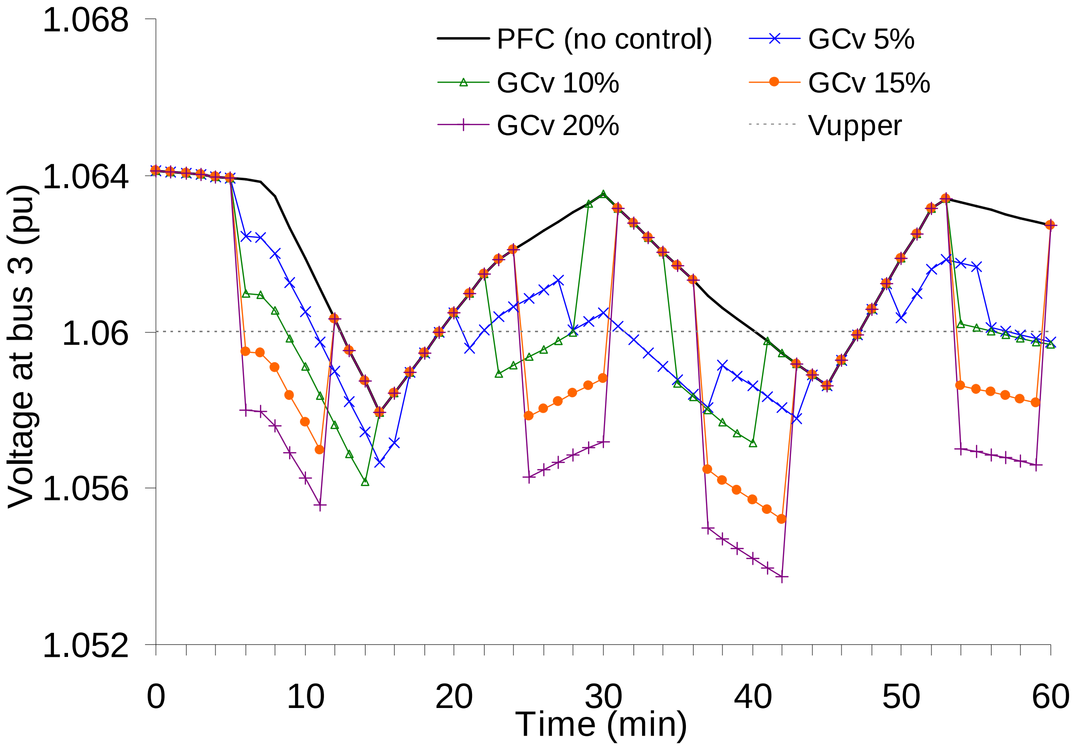



**Figure 4 - 15: Voltage profiles at bus 3 for the voltage management using generation curtailment (GCv) based on the reduction rate**

As demonstrated, the generation curtailment using the reduction rate method is able to overcome the voltage rise impact. Nonetheless, the performance is not precise compared to employing the reactive power control with the sensitivity approach. The validation here is only for the purpose of showing the corresponding control behaviour as the generation curtailment is only used as the last resort for voltage management. This analysis also uses the time delay of 5 minutes. This can be adjusted to more appropriate values depending on network sensitivity and topology. Different control options for the time delay and reduction rate will be examined in detail later.

### 4.8.3 Thermal Management based on Reduction Rate

This subsection demonstrates the line overload management action using the reduction rate method. In the thermal management scheme, the capacity threshold is set to 95% of the maximum capacity of the line. The line flow between buses 2-3 when the wind farm is operating at 6-MW, normal operation is depicted as the studied line flows in Figure 4 - 16. At normal operation (no control), the maximum line-loading limit is already breached at the beginning of the measurement as well as between minutes 20$^{th}$ to 40$^{th}$ and after minute 48$^{th}$ due to a large amount of power being produced at low demand. The pattern is similar to the voltage profile (presented in the previous subsection) due to the wind and demand characteristics. Here, the thermal management scheme based on the reduction rate is demonstrated with four reduction rates examined: 5, 10, 15 and 20%.

As illustrated in Figure 4 - 16, the responses are similar to that for the voltage management in that the smoothness is obtained when the reduction rate is small (5%). The larger reduction rate causes a wider step drop in the line flow as the power output is curtailed. Investigation of different time delay and reduction rate options is presented later. This method provides simple line overload mitigation however the curtailed level does not precisely maintain the maximum line capacity and may be ineffective in the more severe situation when the wind speed is high but variable.

A test was also carried out for the thermal management based on the power output set point method and the mechanism was similar to the reduction rate as presented here, i.e., stepping down of the line flow due to the power output being curtailed and with the time delay to freeze the amount of the line flows below the $S_{Target}$.

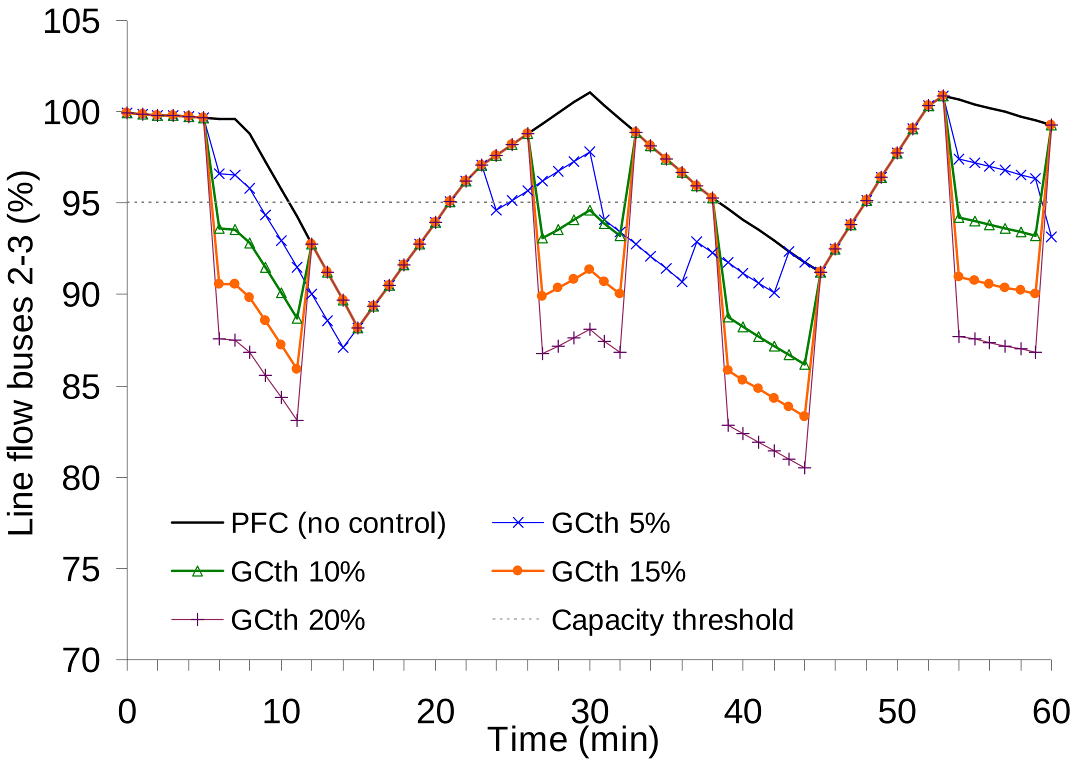



**Figure 4 - 16: Line flow buses 2-3 for the thermal management based on the reduction rate (GCth is generation curtailment for thermal management)**

## 4.9 Validation: Full Scheme

Whilst the simplified wind-demand pattern with perfect forecasting was used in the previous section to clearly illustrate the operation, in this section, validations of the voltage scheme alone, the thermal scheme alone and the joint voltage and thermal management scheme with new, more variable wind and assuming that the availability of load and wind generation forecasts is close to realistic (persistence forecasting) are presented. All schemes employ the sensitivity analysis method where the next period calculated variables are estimated based on the current information. The validations were carried out on a minute-by-minute time step over an hour to capture the voltage rise and line overload problems. The corresponding mitigation actions from each scheme are demonstrated. In all cases, the worst case of minimum demand and maximum wind generation to dictate the problems has been used.

The 33/11kV 3-bus test feeder in Figure 4 - 12 once again is used but with different wind and demand profiles. Demand is maintained at 40% of peak to emphasise voltage rise. The new wind generation profile measured at a site in England (February weekday, 6-7am) shown in Figure 4 - 17 is applied. This period is appropriate for testing the scheme as it represents a worst-case scenario where high wind speeds (and more variability) coincide with minimum demand. The wind farm and the CHP operate at 6 and 3.4-MW capacities.

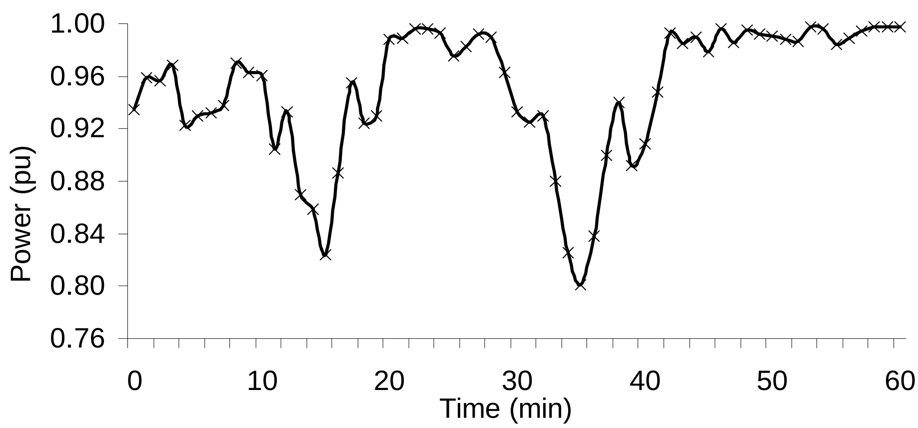



**Figure 4 - 17: 60-minute wind generation profile (pu of nominal capacity)**

### 4.9.1 Voltage Management based on Sensitivity Analysis

To examine the impact of voltage management, the case without control is compared with the voltage control scheme alone. The voltage threshold and target are respectively set at 0.15 and 0.25 percentage points below the upper voltage limit (1.0585 and 1.0575pu). The wind farm ramp rate is assumed as 1-MW per minute. The conservative values adopted avoided excessive overloads for the specific wind variability, network impedances, voltage and power flow sensitivity and the action of the OLTC. However, the settings are intended to be tailored to other networks to deliver more or less conservative constraints on voltage and power flows. The effect of thermal constraint is ignored in order to examine the voltage mitigation action.

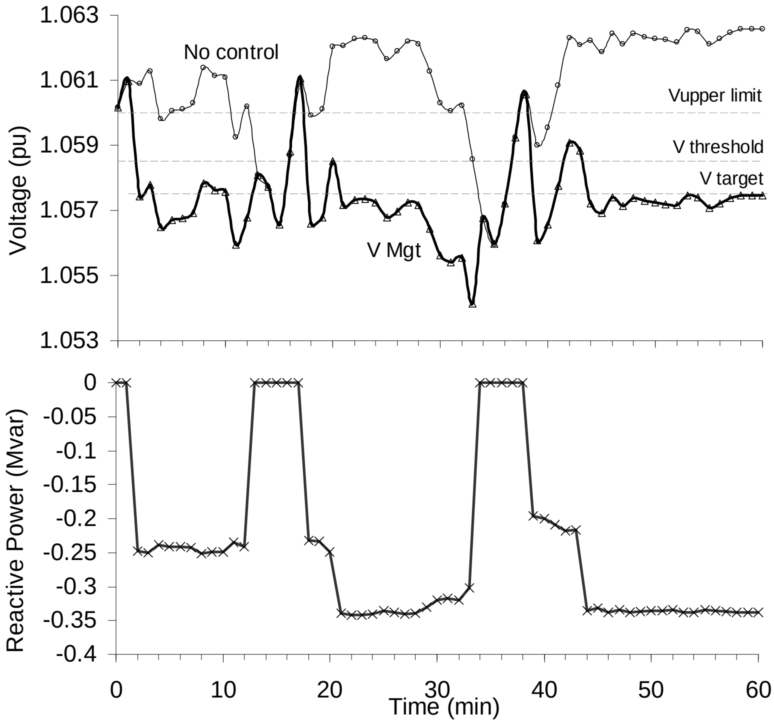



**Figure 4 - 18: (Top) Voltage profile at bus 3 applying the voltage management scheme (V Mgt) and (bottom) reactive power absorbed by the wind farm**

The voltage profile at bus 3 with and without the voltage management scheme (V Mgt) is illustrated in Figure 4 - 18 (top). When voltage exceeds the threshold, the scheme is activated. For instance, voltage at minute 1 (1.061pu) exceeds the threshold. The first action is to calculate the voltage sensitivity at that instant. A snapshot power flow of the network state at minute 1 is used to calculate the voltage drop resulting from the absorption of 1-Mvar by the wind farm. The voltage sensitivity, 0.0148 pu/Mvar in this case, is then used with Equation 4 - 2 to estimate the change in reactive power necessary to reduce the voltage to the target. Thus, the required (inductive) reactive power for minute 2 can be estimated as:

$$\Delta Q = \frac{1.061pu - 1.0575pu}{0.0148pu} = 0.24\ MVar$$

This value is negative in Figure 4 - 18 as reactive power is absorbed.

Where the voltage is below the threshold value, the wind farm continues to operate at the adjusted power factor until the wind speed increases or decreases (demand is constant). In the former case voltage may rise above the threshold prompting a new, more inductive, set point, as shown for minutes 21 to 33 in Figure 4 - 18 (bottom). Where wind drops, the farm adjusts to unity power factor operation (e.g. minutes 13 to 17). In this way, the voltage is maintained around the target value for extended periods. For this test period, the reactive power capability was sufficient and generation curtailment was not required for voltage management. The analysis accounts for the reduction in the reactive capability of double fed induction generators as the wind output drops.

### 4.9.2 Thermal Management based on Sensitivity Analysis

The same network and demand conditions as for the validation of the sensitivity method voltage management are used to demonstrate the control actions of the thermal scheme based on the sensitivity analysis. The line flow threshold and target are set to 4.5% and 5% below capacity (based on 100% nominal capacity), respectively. In this case, the effect of voltage limitation is ignored so as to examine the response of the thermal overload management.

The pattern of line usage with and without the thermal constraint management is depicted in Figure 4 - 19 (top). Similar to voltage (Figure 4 - 18) line loading varies with wind power injection. Without control, the line flows reach and exceed the line capacity. When the power flow exceeds the capacity threshold, the control scheme is activated and actions the wind farm to trim its power output to a new generation level (Figure 4 - 19 (middle)) to maintain the loading at the line flow target. The effect of the generation curtailment in the thermal management scheme on the voltage profile at bus 3 is shown in Figure 4 - 19 (bottom). The pattern is similar to the line flow as a result of the active power control.

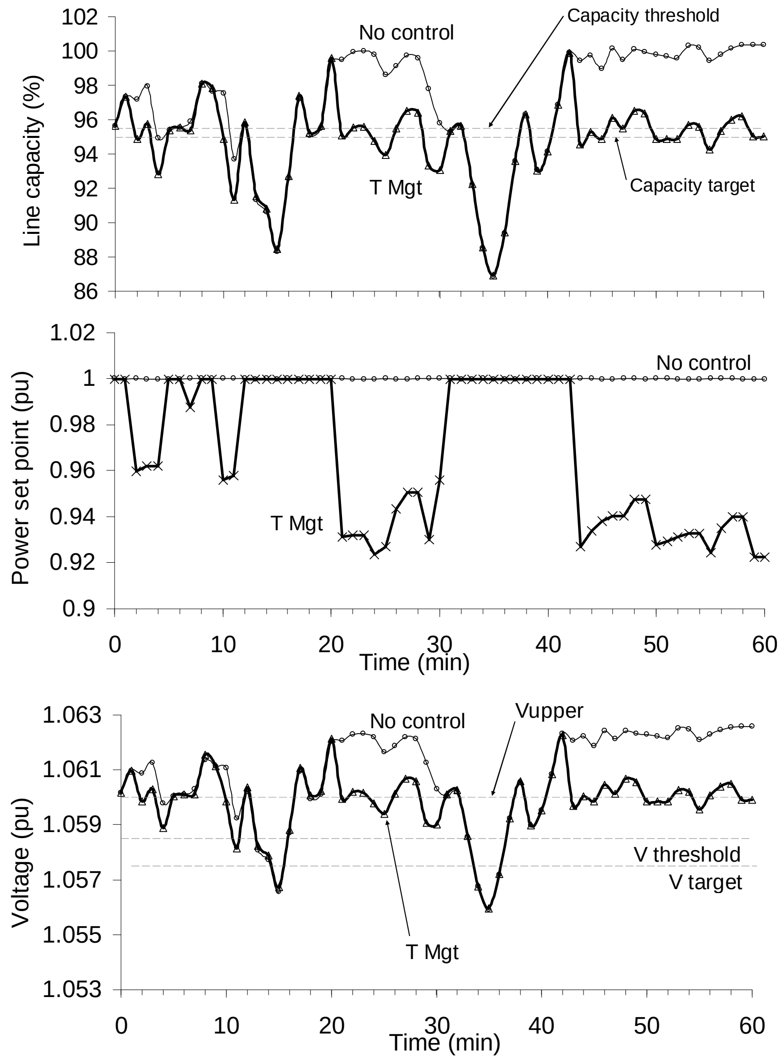



**Figure 4 - 19: (Top) Capacity usage of line 2-3 with the thermal management scheme (T Mgt); (middle) wind farm power set point (pu of nominal capacity); and (bottom) voltage profile at bus 3 under the thermal management**

The sensitivity calculation is performed in a similar way to the V Mgt. At minute 1, the line loading (97.3%) exceeds the threshold. A snapshot analysis indicates that curtailing 1-MW from the wind farm lowers line loading by 11.3%. Using Equation (4-7), the loading sensitivity is used to calculate the real power to be trimmed to meet the target loading (95%):

$$\Delta P_{t=1} = \frac{97.33\% - 95\%}{11.3\% / MW} = 0.21 MW$$

In minute 1, a power output of 5.75-MW means the trimming instruction would lower the power output to 5.54-MW ($W_{t=1}$ is 0.96pu). This resulting power set point according to Equation (4 - 4) for minute 2 is:

$$SP_{t=2} = \frac{5.54 MW}{0.96 pu \times 6 MW} = 0.96$$

With actual wind production in minute 2, $W_{t=2}$, slightly lower than forecast (0.956pu), line loading undershoots the target to 94.85%. The scheme will respond by calculating a higher set point for minute 3 to take advantage of the extra headroom. With an updated sensitivity of 11.25%/MW and instantaneous power output of 5.508-MW, $SP_{t=3}$ is:

$$\Delta P_{t=2} = \frac{94.85\% - 95\%}{11.25\% / MW} = -0.013 MW$$

$$SP_{t=3} = \frac{5.508 MW - (-0.013 MW)}{0.956 pu \times 6 MW} = 0.962$$

With this set point the actual line capacity in minute 3 was observed at slightly above the threshold due to a small wind increase. The process then repeats to produce a new set point for minute 4. At this point, wind production dropped enough for line flow to fall below the threshold, prompting a higher set point to be estimated, which in this case, was a return to ‘normal’ unconstrained operation in minutes 5 to 6 ($SP_{t=5}$ = 1).

### 4.9.3 Joint Voltage and Thermal Management based on Sensitivity Analysis

Plots of voltage profiles, power output, line loading and active and reactive set points as a result of the joint V&T Mgt are depicted in Figure 4 - 20 and Figure 4 - 21. In this case voltage rise and high line loading occur together with priority given to thermal constraint management. It can be seen that when the thermal management scheme is activated (e.g., minutes 1 to 4) the voltage profile follows a similar pattern to line loading. In minute 5 the line flow is maintained below its threshold, but voltage remains above its own threshold. Voltage management is activated resulting in an inductive power factor set point that lowers the voltage. The wind farm operates with these set points until minute 8 when the wind speed increases forcing the thermal management scheme to issue a new active power set point. In the next period the wind speed drops causing line flow to fall 4 percentage points below the target. With this extra headroom, the scheme reacts to increase the active power set point to unity. The power set point behaviour is similar to that in Figure 4 - 19 due to the thermal control priority. The active power curtailment with in the thermal management scheme is seen to assist in lowering voltages. Consequently, the reactive power required to manage voltage rise is less than for the voltage management scheme alone (Figure 4 - 20 (bottom)).

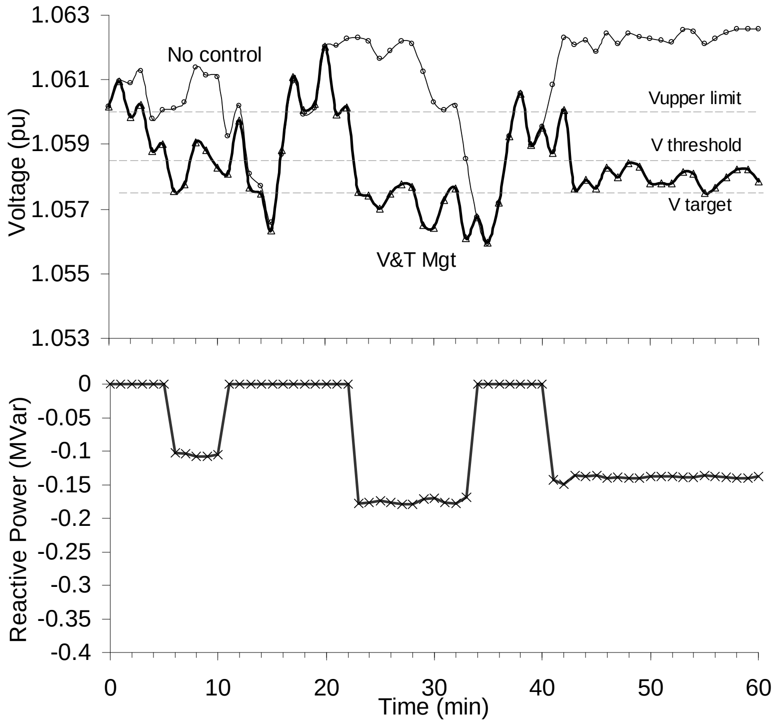



**Figure 4 - 20: (Top) Voltage profiles at bus A and (bottom) wind farm's reactive power using the voltage and thermal constraint management (V&T Mgt)**

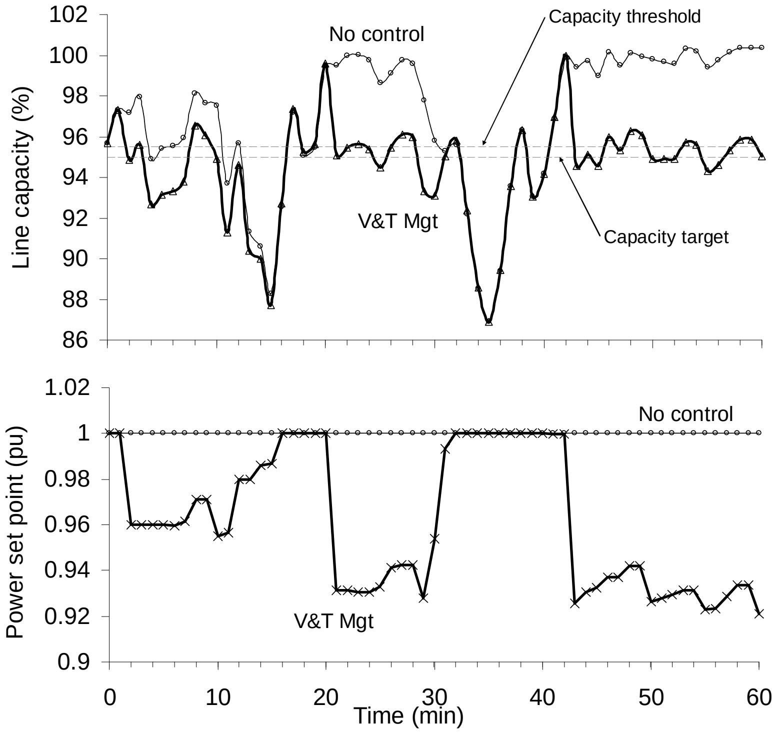



**Figure 4 - 21: (Top) Capacity usage of line 2-3 and (bottom) wind farm's power set point using the voltage and thermal constraint management (V&T Mgt)**

## 4.10 Comparison of Methods

The comparison in this section is divided into two parts. Firstly, different control options and settings for the decentralised voltage and thermal management with perfect wind and demand forecasts are investigated. Comparison between each option on the basis of energy export and system losses is provided and the advantages and disadvantages of different options are also summarised. Secondly, a comparison between the perfect and persistence forecast situations are investigated and discussed. The analyses in both parts were carried out using again the 3-bus test feeder with the more complex demand and wind generation profile used earlier.

In the first part of the comparison, a series of control options for the voltage and thermal management schemes with selected settings are tested. One base case and six control options denoted A, B1, B2, C1, C2, D1 and D2, as shown in Table 4 - 4, are explored. Option A is a base case where a generator operates in a unity, fixed power factor mode. Options B1 and B2 present voltage management based on two different methods for the active power curtailment: reduction rate and sensitivity analysis. Options C1 and C2 are for thermal management also adopting the reduction rate method and the sensitivity analysis, respectively. For the thermal management, the effects of different reduction rates and time delays are also explored. Options D1 and D2 are the joint voltage and thermal management with the reactive power control using the sensitivity analysis and the active power curtailment based on the reduction rate (option D1) and sensitivity methods (option D2), respectively. The control settings requirement for each option is also summarised in Table 4 - 4. The results are presented and discussed in the next subsections.

**Table 4 - 4: Description, settings and values of the control options to be investigated (voltage upper limit is 1.06pu and maximum line capacity is 100%)**

| Options | Schemes | Description | Settings | Values |
|---|---|---|---|---|
| A | No control | • Fixed power factor (unity) without control | None | None |
| B1 | V Mgt ($\frac{\partial V}{\partial Q}$, % trim) | • Reactive power control based on sensitivity analysis<br>• Active power curtailment based on reduction rate<br>• Line overload ignored | $V_{Threshold}$<br>Reduction rate<br>$T_{Delay}$<br>PF capability | 1.0585pu<br>10%<br>5 minutes<br>0.95 ind/cap |
| B2 | V Mgt ($\frac{\partial V}{\partial Q}$, $\frac{\partial V}{\partial P}$) | • Reactive power control and active power curtailment based on sensitivity analysis<br>• Line overload ignored | $V_{Threshold}$<br>$V_{Target}$<br>Power factor capability | 1.0585pu<br>1.0575pu<br>0.95 ind/cap |
| C1 | T Mgt (% trim) | • Active power curtailment based on reduction rate<br>• Voltage rise ignored | $S_{Threshold}$<br>Reduction rate<br>$T_{Delay}$ | 95.5%<br>10%<br>5 minutes |
| C2 | T Mgt ($\frac{\partial S}{\partial P}$) | • Active power curtailment based on sensitivity analysis<br>• Voltage rise ignored | $S_{Threshold}$<br>$S_{Target}$ | 95.5%<br>95% |
| D1 | V&T Mgt ($\frac{\partial V}{\partial Q}$, % trim) | • V Mgt – Reactive power control based on sensitivity analysis and active power curtailment based on reduction rate<br>• T Mgt – Active power curtailment based on reduction rate | $V_{Threshold}$<br>PF capability<br>$S_{Threshold}$<br>Reduction rate<br>$T_{Delay}$ | 1.0585pu<br>0.95 ind/cap<br>95.5%<br>10%<br>5 minutes |
| D2 | V&T Mgt ($\frac{\partial V}{\partial Q}$, $\frac{\partial V}{\partial P}$, $\frac{\partial S}{\partial P}$) | • V Mgt – Reactive power control and Active power curtailment based on sensitivity analysis<br>• T Mgt – Active power curtailment based on sensitivity analysis | $V_{Threshold}$<br>$V_{Target}$<br>PF capability<br>$S_{Threshold}$<br>$S_{Target}$ | 1.0585pu<br>1.0575pu<br>0.95 ind/cap<br>95.5%<br>95% |

### 4.10.1 Results: Individual Voltage/Thermal Management (B1, B2, C1, C2)

For the voltage management, options B1 and B2 assuming that the thermal constraint is ignored, both options are able to effectively manage the voltage rise but only the reactive power control was used. This is because the voltage rise can be overcome by the reactive power capability of the DG unit. The control mechanisms are similar to that in the validation of voltage management (Section 3.8.0).

The thermal management using the reduction rate with time delay and the sensitivity methods are investigated in options C1 and C2 (with the voltage rise impact ignored). For the control settings of option C1 (i.e., 10% reduction rate and 5 minutes time delay), the values were chosen by judgement based on the comparison between control performance, power output and system losses occurring at selected reduction rates and time delays prior to the simulations. Sensitivity study for different reduction rates and time delays is investigated in the followings:

**Effect of Varied Percentage Reduction Rate**

The first parameter tested was the effect of percentage reduction rate on performance of thermal management (option C1). Three reduction rates range from 5% to 20% in addition to the 10% base value were applied with a fixed 5-minute delay. The results are presented in Table 4 - 5.

It was found that the different settings did not affect the period of line overload but had an influence on energy export and losses. Setting the reduction rate to 5% increased the export benefit by 20%, where losses increased marginally. Using a 20% rate severely affected export levels, reducing the benefit of the control by two-thirds.

**Sensitivity Study: Effect of Varied Time Delays**

The second parameter tested was the time delay for option C1 which were adjusted from 5 minutes to between 1 and 7 minutes. A short delay time raised the period of line overload to 11.7% (from 3.3%) whereas an extended time delay had no effect. However the shorter delay time promoted greater MWh export benefit, increase by 20% for the 1-minute time delay.

Comparison of the control actions for options C1 and C2 are depicted in Figure 4 - 22. Both options are able to provide immediate and effective responses to the line overload impact. Nonetheless, a more precise control action is seen from adopting option C2 (using the thermal sensitivity analysis) compared to option C1.

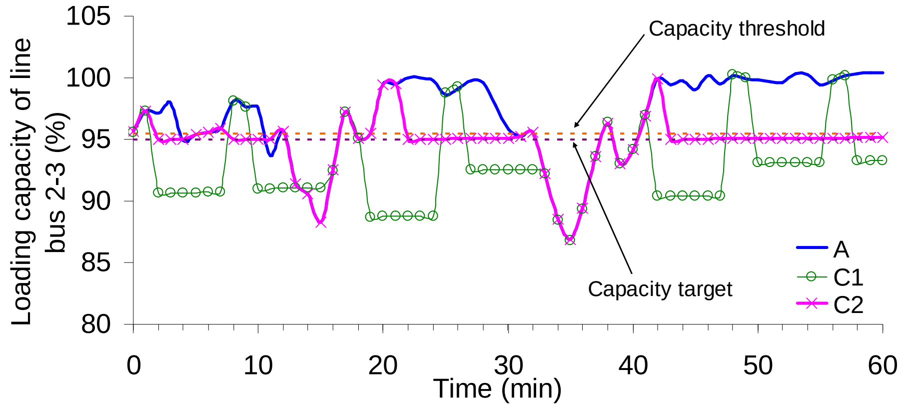



**Figure 4 - 22: Line loading between buses 2-3 for options A, C1 and C2**

### 4.10.2 Results: Joint Management (D1 and D2)

The joint management to overcome both the voltage rise and line overload impacts that occur simultaneously is demonstrated in options D1 and D2. In option D1, the same settings as for options B1 and C1 are applied. Similarly, the settings for options B2 and C2 are used for option D2 (Table 4 - 4).

Voltage profiles at bus 3 and line 2-3 flows for options D1 and D2 are shown in Figure 4 - 23 and Figure 4 - 24, respectively. Both options reveal effective responses to mitigate the voltage rise and thermal overload that occurred either individually or at the same time. In option C1, the action is straightforward following the control commands. In contrast, option D2 provides more prompt and precise control action as the voltage and thermal capacity sensitivities are calculated in real-time. As seen from both options, the performance is not as effective as adopting the individual scheme to mitigate a single constraint (option B or Option C). However, the schemes are able to effectively and instantly manage both constraints and provide sufficient control to ensure security of the feeder operation while being able to accommodate more DG penetration.

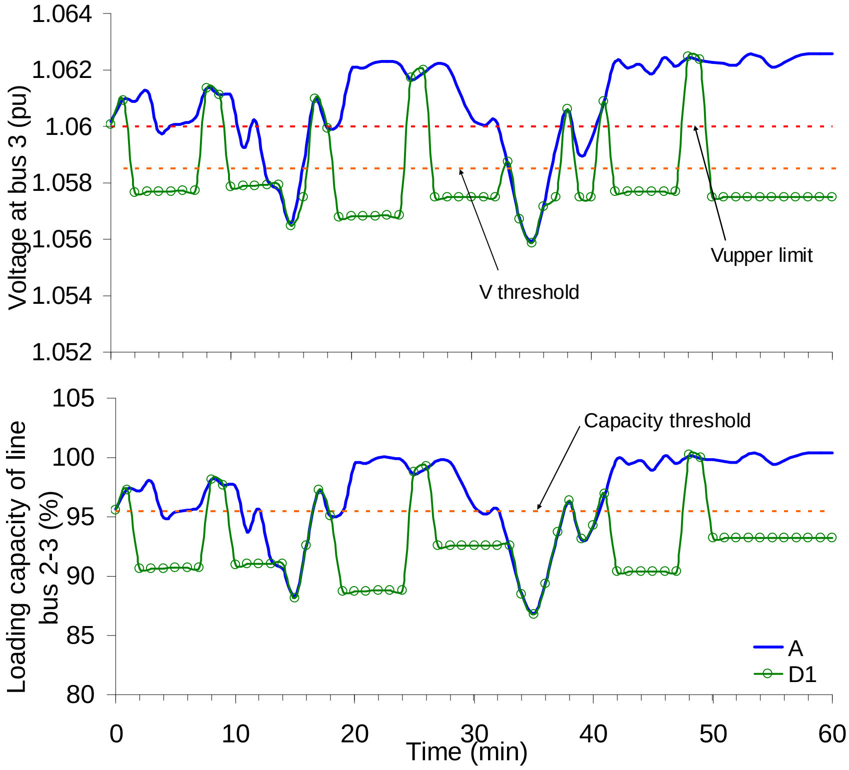



**Figure 4 - 23: (Top) voltage profile at bus 3 in pu and (bottom) percentage of line flows buses 2-3 for option D1**

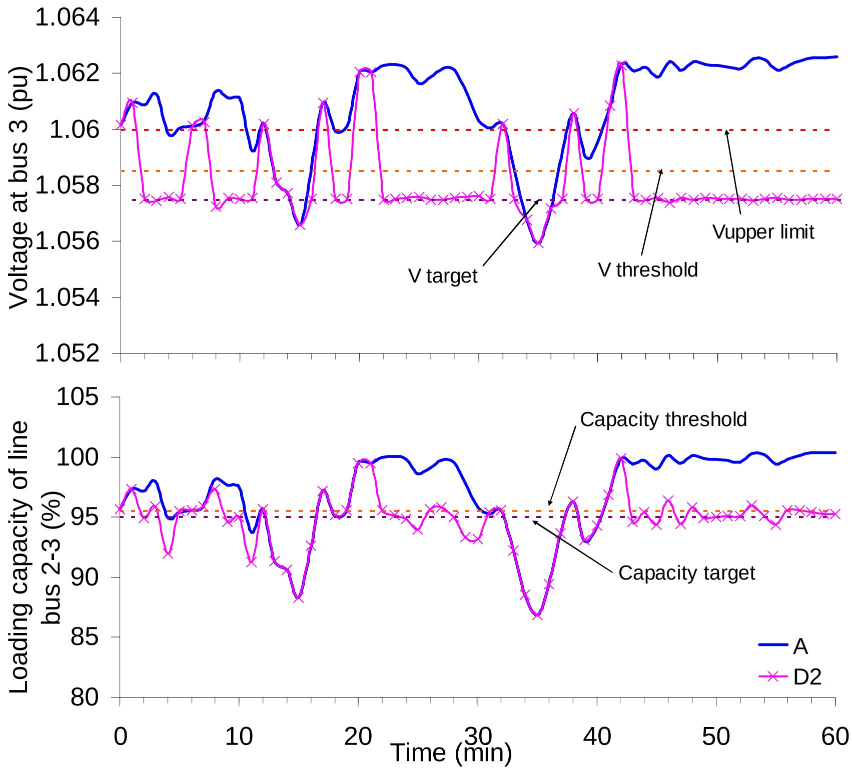



**Figure 4 - 24: (Top) voltage profile at bus 3 in pu and (bottom) percentage of line flows buses 2-3 for option D2**

### 4.10.3 Overall Performance Comparison

Overall performance of options B1 to D2 on the basis of the ability to manage the constraints, energy exports and system losses is compared in Table 4 - 5. In option A, increasing the wind capacity from 5-MW (fit & forget approach) to 6-MW clearly raises the risk of voltage rise and overload of line capacity by around 78% and 15%, respectively. If the voltage rise was the only key impact, adopting options B1 and B2 could mitigate the voltage rise effectively. In terms of the energy exports and losses, option B2 yields a slightly higher export but causes more losses than those obtained by option B1. Similarly, if the thermal overload impact was the only limiting factor, options C1 (10%, 5 minutes) and C2 could be implemented. As shown, option C2 provides better performance against the line overload problem and yields higher energy export than employing option C1 (10%, 5 minutes). However, option C2 causes around 7% higher system losses than adopting option C1 (10%, 5 minutes).

**Table 4 - 5: Overall performance based on periods of voltage rise, periods of line overload occurrence, total energy export and total system energy losses (hour-long simulation period)**

| Options | Periods of voltage rise (%) | Periods of line overload (%) | Total MWh export (% increase) | Total MWh system losses (% increase) |
|---|---|---|---|---|
| A (5-MW) | None | None | None | None |
| A (6-MW) | 78.3% | 15% | 20% | 26.5% |
| B1 | None | N/A | 19.8% | 25.2% |
| B2 | None | N/A | 19.9% | 26.9% |
| C1-5% 5 minutes | N/A | 3.3% | 14.7% | 17.5% |
| C1-10% 5 minutes (base case) | N/A | 3.3% | 12.3% | 14.3% |
| C1-15% 5 minutes | N/A | 3.3% | 8.4% | 9.3% |
| C1-20% 5 minutes | N/A | 3.3% | 4.6% | 4.4% |
| C1-10% 1 minute | N/A | 11.7% | 15.4% | 18.6% |
| C1-10% 3 minutes | N/A | 10% | 13.4% | 15.9% |
| C1-10% 7 minutes | N/A | 3.3% | 12% | 14% |
| C2 | N/A | None | 16% | 20.8% |
| D1 | 18.3% | 1.7% | 11.8% | 13.7% |
| D2 | 20% | None | 15.6% | 20.6% |

Realistically, for the voltage and line flows constraints (occurring at the same time) caused by the increased capacity of wind are coped with using options D1 and D2. As summarised in Table 4 - 5, option D1 performed more effectively in response to the voltage rise but could not completely mitigate the overload of line due to the time delay mechanism. However, the occurrence period is relatively short and may be ignored. In terms of the power output and losses, option D2 results in a slightly higher output but losses increase.

It is also found that the overall performance of the scheme to cope with the voltage rise and the thermal overload (option D) is not as effective as when dealing with only one impact (options B or C), taking into account the control capability. However, in reality, both constraints must be managed to ensure security operation of the distribution network. This presents a trade-off where the mitigation capability has to be shared between the two constraints while more capacity of DG can be connected. In addition, the schemes with the sensitivity method (options B2, C2 and D2) yield more power output but higher system losses than those with the trim target method. Therefore, choosing which option to be implemented will depend on decisions and agreements between particular network operators, DG developers and third parties.

### 4.10.4 Perfect vs Persistence Forecasting

In the second part of the comparison, the influence of having perfect and persistence wind and demand forecast on the joint voltage and thermal management schemes is explored. The aim is to compare the voltage and line flow control behaviours as a result of employing the joint voltage and thermal management, both based on the sensitivity analysis, when the demand and wind forecast is and is not available. The full scheme (option D2) was retested assuming perfect forecast. The persistence forecast case V&T Mgt in Section 4.9.3 was used.

For voltage, as illustrated in Figure 4 - 25 (top), it is clearly seen that the management scheme in a perfect environment for demand and wind forecast performs more precise control compared to that with persistence forecast. With persistence, the estimation deviates from the target value whereas these errors are not an issue for the case with forecast.

For line flow, the control actions from both assumptions (as shown in Figure 4 - 25 (bottom)) are similar. This is due to the effect of the reactive power control that adds to the line flows. The benefit of having wind and demand forecast available could enhance the control performance for both the voltage rise and line overload mitigation.

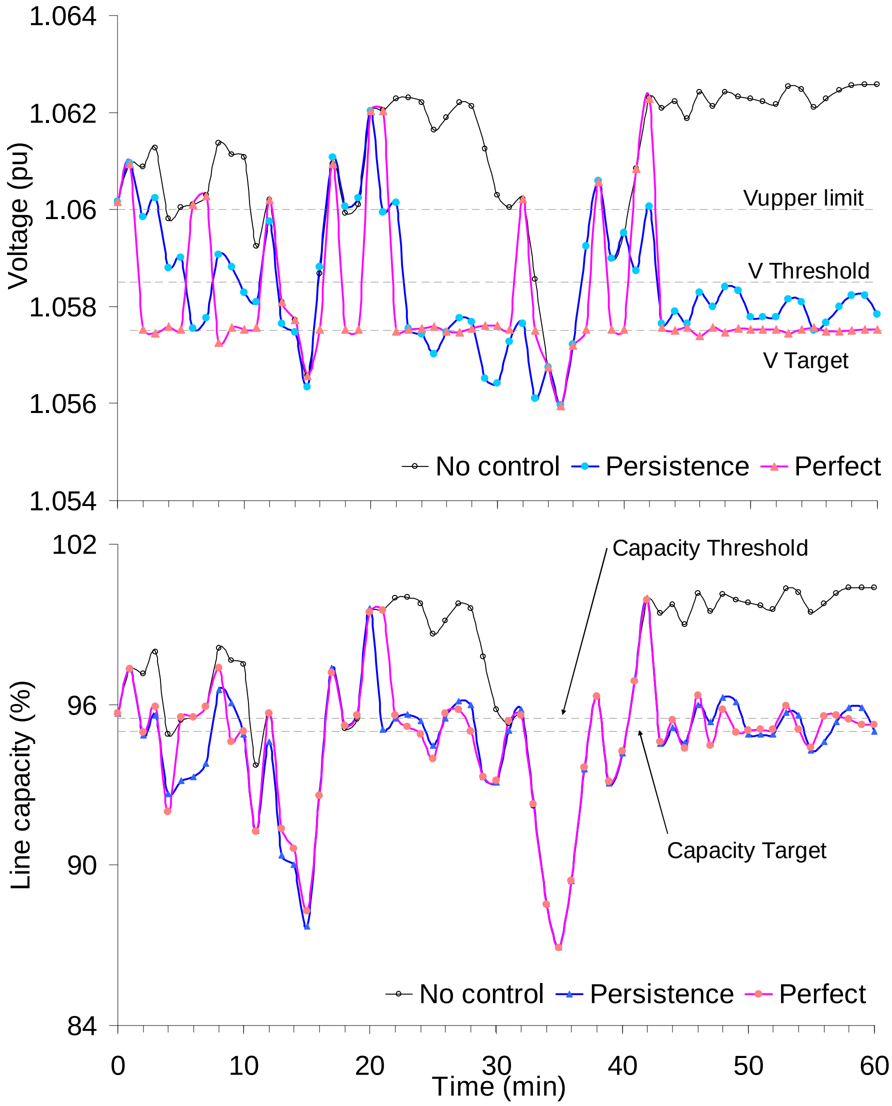



**Figure 4 - 25: Comparison of (top) voltage profiles and (bottom) line flows for the management scheme with perfect and persistence forecasts**

### 4.10.5 Risks and Benefits Comparison

Validation and performance of the voltage and thermal management options have been presented and discussed the previous subsections. This section will summarise and compare the benefits, risks, control settings and measurement requirement for each control option. The summary is given in Table 4 - 6 for options B1, B2, C1 and C2. This can also be seen as guideline in assisting the DNOs and DG developers when choosing appropriate control scheme.

For the voltage rise management, options B1 and B2 can provide effective responses to the voltage rise in real-time. However, both options are limited by the reactive power capability, size and type of a generator and requirement from DNOs. The scheme may also increase the risk of line overload due to the reactive power being absorbed by the DG unit. In option B1, the generation curtailment voltage using the trim target method is simpler in its mechanism and does not require continuous calculations. However, the adjustment for the reduction rate and the time delay prior to adopting the scheme is required. Option B2 provides more precise and instantaneous voltage control as it utilises the voltage sensitivity method for each measurement cycle. For thermal overload management, options C1 and C2 can effectively mitigate the overload impact. Comparisons for the benefits and risks between options C1 and C2 are similar to those discussed for options B1 and B2. The sensitivity analysis method for the thermal management also has an advantage over the others in that it could avoid unnecessary power curtailment losses compared to the reduction rate method.

In terms of forecasting, the information for demand and wind forecast has an influence on the control performance. A perfect forecast enables more precise control over both voltage and line overload constraints compared to the persistence case. Such information may be difficult to obtain for a scheme meant to be decentralised however the scheme with the persistence environment also provided effective constraint management.

**Table 4 - 6: Summary of benefits, risks and settings requirement of each control option**

| Options | Benefits | Risks/Disadvantages | Measurement/Data Requirement | Settings Requirement |
|---|---|---|---|---|
| B1 | • Effective voltage rise mitigation<br>• Simple control<br>• No calculation required each cycle<br>• Could reduce losses in curtailment | • Limited by the reactive power capability, size of a generator and DNOs requirement<br>• Generation curtailment not precise control<br>• Need adjustment of settings (reduction rate and time delay)<br>• Can increase thermal overload impact due to Q flow | • Bus voltage<br>• Network data<br>• Wind and demand forecast | • Voltage threshold<br>• Time delay |
| B2 | • Effective voltage rise mitigation<br>• Precise and real-time control<br>• Quicker response to problem<br>• Could reduce losses in curtailment | • Limited by the reactive power capability, size of a generator and DNOs requirement<br>• Require continuous calculation of sensitivity and calculation errors<br>• Can increase thermal overload impact due to Q flow | • Bus voltage<br>• Sensitivity calculations<br>• Network data<br>• Wind and demand forecast | • Voltage threshold<br>• Voltage target |
| C1 | • Effective thermal overload mitigation<br>• Simple control<br>• No sensitivity calculation required<br>• Large reduction rate could reduce system losses | • Limited by size of a generator and DNOs requirement<br>• Not precise control and slow action<br>• Need adjustment of settings (reduction rate and time delay)<br>• Losses in curtailment | • Line flow<br>• Network data<br>• Wind and demand forecast | • Capacity threshold<br>• Time delay |
| C2 | • More precise and effective thermal overload mitigation<br>• Reduce unnecessary power lost in curtailment<br>• Quicker response to problem | • Limited by size of a generator and DNOs requirement<br>• Require continuous calculation of sensitivity and calculation errors<br>• Losses in curtailment | • Line flow<br>• Sensitivity calculations<br>• Network data<br>• Wind and demand forecast | • Capacity threshold<br>• Capacity target |

## 4.11 Full Case Study: Joint Decentralised Voltage and Thermal Management

In this section, the joint voltage and thermal management scheme is extended to a more realistic network to assess the effectiveness for voltage and thermal constraints that occur with variations in both load and generation. The controls are applied to two wind farms in order to examine the behaviour with multiple DG plants. The simulation and performance assessment are carried out in a 10-minute time step over one year on the basis of its ability to manage both constraints simultaneously and in terms of the exported energy.

### 4.11.1 Network, Load and Generation

Figure 4 - 26 shows a modified 12-bus rural distribution network obtained from the UK Generic Distribution System [120]. The network parameters are provided in Appendix A. For the purpose of increasing voltage and power flow sensitivity suitable for the constraints study, buses 13 to 16 and the voltage regulator between buses 8 and 9 present in the original system are omitted. The peak demand is 36.6-MW. The CHP unit at bus 12 is not actively controlled and operates at constant 3.5-MW and 0.97 inductive power factor. The two wind sites at buses 11 and 12 are geographically close but distant enough to have different wind profiles. Demand and wind speed data for central Scotland in 2003 was used and wind production was estimated using a generic wind power curve [119]. It is assumed that the wind resource at bus 12 is better than at bus 11 with capacity factors of 0.45 and 0.41, respectively.

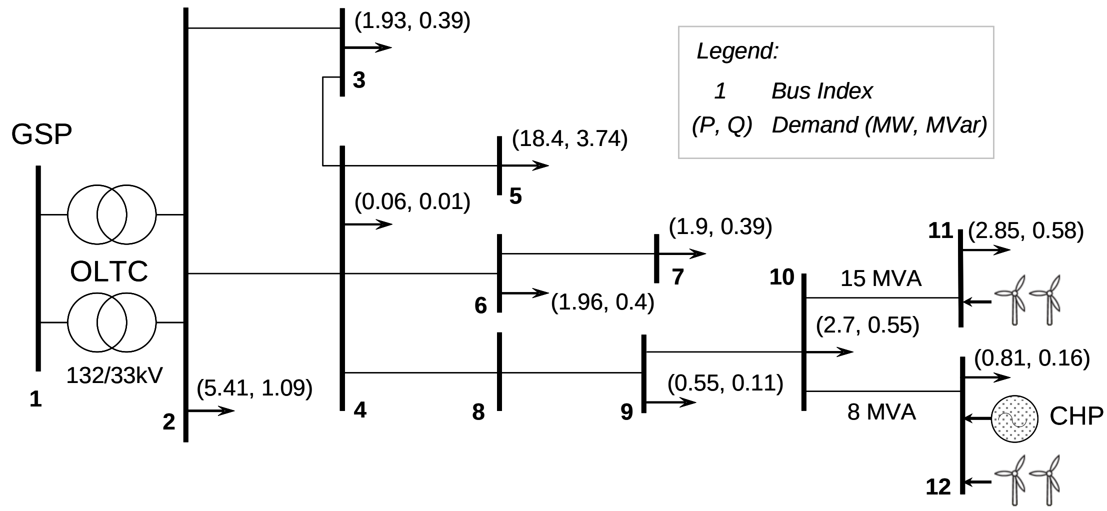



**Figure 4 - 26: Modified 12-bus 33kV rural distribution network (UK GDS [120]).**

### 4.11.2 Joint Voltage and Thermal Management in Action

With the fit-and-forget operation the network can host around 3-MW of capacity at each wind site. Raising the capacity at each site will tend to create over-voltages at the connection buses 11 and 12 and overload lines 10-11 and 10-12. To demonstrate that the decentralised constraint management scheme can increase the connection of new generation capacity without compromising network operation, 6-MW of wind capacity is accommodated at each site and operates at unity power factor. To illustrate a full range of wind generation and demand combinations a one-year window at a 10-minute time step is analysed. Actual implementation would be at much smaller time steps.

To show how the control mechanisms interact, a 5-day sample window depicting summer minimum demand is illustrated. Wind production and demand during the period is shown in Figure 4 - 27. Time-series results for voltage at bus 12 and the loading of line 10-12 are shown in Figure 4 - 28 and Figure 4 - 29, respectively. The better wind resource and lower demand at bus 12 and the lower capacity of line 10-12 make control action impacts more significant than at bus 11. As such, samples for bus 11 are omitted.

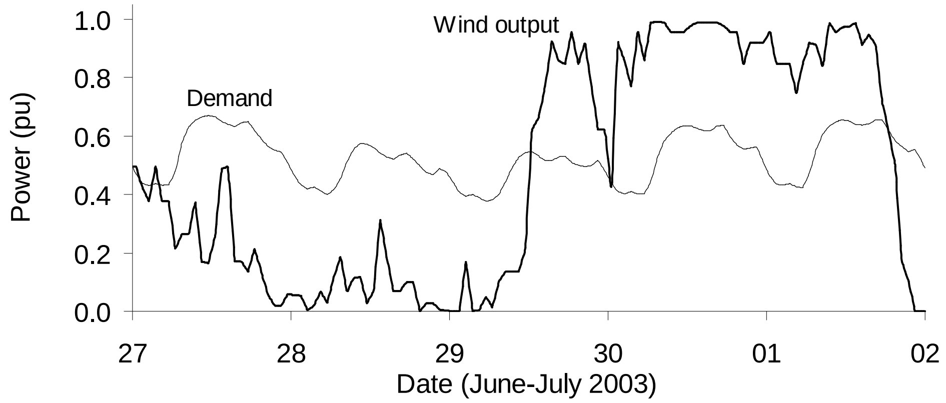



**Figure 4 - 27: 5-day plot for wind power output (pu of nominal capacity)**

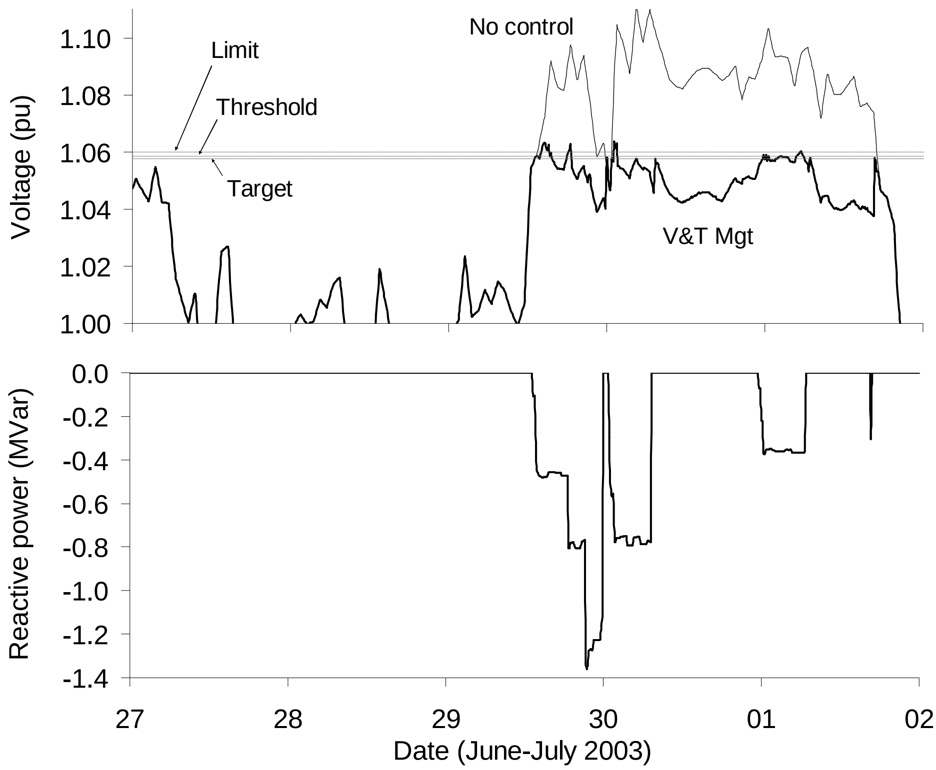



**Figure 4 - 28: (Top) 5-day plots of voltage profile and (bottom) reactive power output at bus 12 for no control and V&T Mgt**

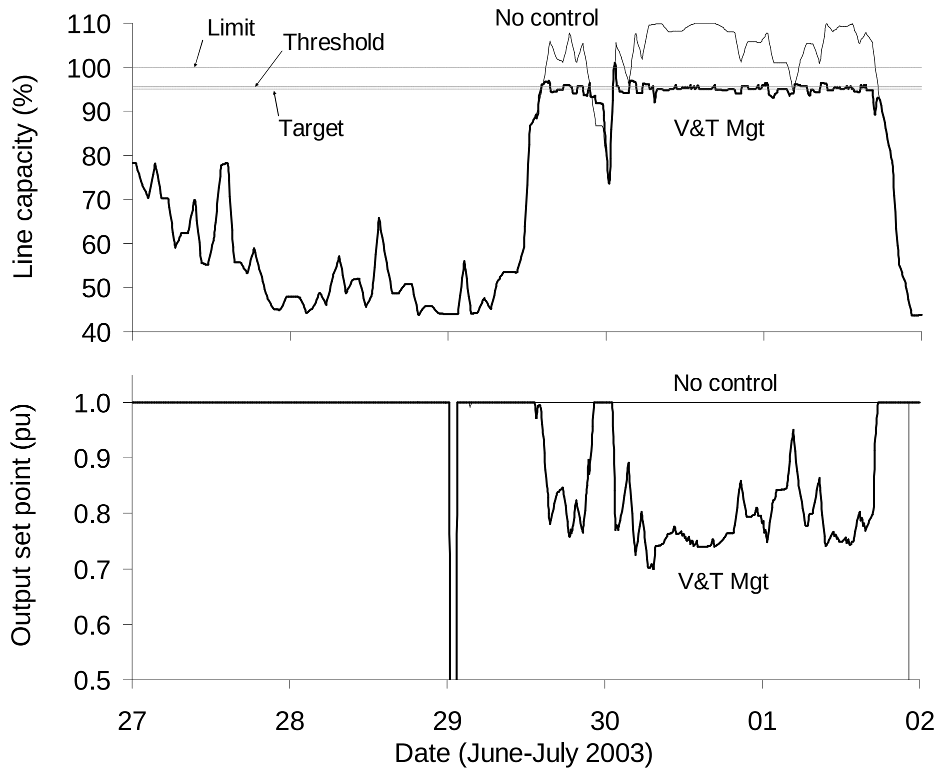



**Figure 4 - 29: (Top) 5-day plots of line powers for line 10-12 and (bottom) set point of the wind farm for no control and V&T Mgt**

Over the first two days the wind speeds are relatively low and voltage and line flows stay within their thresholds. High wind speeds in the second half of the period (29$^{th}$ June onwards) results in simultaneous voltage rise and line loading impacts, requiring actions from the generation curtailment and the reactive power controls. Note that the drop in power output to zero on 29$^{th}$June is due to the momentary absence of wind (Figure 4 - 27). The main control action over the severe period was thermal management and line flow was maintained around the target value to ensure the high wind power could be securely delivered. The voltage at bus 12 over the severe period was also effectively managed within the voltage limits. The (inductive) reactive power used for V Mgt was not required as extensively given the relief brought by the generation curtailment.

Figure 4 - 28 and Figure 4 - 29 show that with fit-and-forget operation 6-MW farms at buses 11 and 12 would cause severe voltage rise and overloads. However, as Table 4 - 7 shows, the voltage and thermal management scheme effectively handled both

constraints allowing secure connection of 6-MW of new wind capacity. Although some voltage rise at bus 12 and overloading of the line 10-12 remains, the duration and magnitudes were very small. The capacity of line 10-11 was sufficient to accommodate the 6-MW wind farm; therefore, the thermal overload impact at that location was not an issue.

Table 4 - 7 also shows that, compared to the fit-and-forget approach, the control scheme raises the wind energy yield by almost 100% and 72% at the wind farms at buses 11 and 12, respectively. The capacity factors, which offer a proxy for the economics of wind developments, are impacted differently: marginally at bus 11, but with a reduction of 15% at bus 12. Voltage and thermal constraints at the latter are more significant, driving more curtailment and smaller capacity factor. The financial aspects will ultimately dictate whether a development using the proposed active management approach is feasible or not.

**Table 4 - 7: Full year assessment: periods of voltage rise and line overload, exported energy and wind capacity factor.**

| Cases | No control<br>2 × 3-MW | V&T Mgt<br>2 × 6-MW |
|---|---|---|
| Overvoltage Bus 11 | None | None |
| Overvoltage Bus 12 | 0.21% | 2.4% |
| Overload Line 10-11 | None | None |
| Overload Line 10-12 | None | 0.1% |
| Energy export Bus 11 | 10.8GWh/year | 21.71 GWh/year |
| Energy export Bus 12 | 12.6GWh/year | 21.69 GWh/year |
| Capacity factor Bus 11 | 0.41 | 0.41 |
| Capacity factor Bus 12 | 0.45 | 0.41 |

## 4.12 Chapter Four Summary

This chapter presents the philosophy of the decentralised V&T Mgt scheme to provide real-time, corrective control actions of voltage rise as well as thermal overload, the two most significant technical issues that limit DG penetration. The proposed V&T Mgt scheme is initially based loosely on an existing voltage control that is mainly concerned with voltage rise management of a single generator connected to a distribution network. The scheme has been extended to incorporate DG capabilities for active and reactive power regulation in a way that are able to locally tackle voltage and thermal constraints that occur close to the DG connection point.

The core algorithms are based on reactive power control and active power curtailment (only as a last resort for the voltage management) and employ a series of approaches: the voltage and thermal sensitivities; the reduction rate enforced time delay and the thermal set point (for the thermal management). Threshold, target and time delay values have been introduced as a means of performing effective corrective actions.

The joint V&T Mgt scheme shows its effectiveness in handling the constraints locally where access to wide area measurements, data and communication is limited. The scheme also provides a basis for the coordination of the real-time voltage and thermal constraints management. This approach can be applied to any DG unit, particularly variable sources, where active and reactive power regulation is allowed. In the case of wind turbines connected to a distribution network, voltage as well as line power flow can fluctuate due to the variability of wind. This can cause short-term voltage and line capacity exceeding the thresholds. In practice, voltage and line capacity are allowed to exceed the maximum statutory limits for a certain period of time whilst the network security and performance are still maintained. This will depend on factors such as location, network requirements and weather conditions. For these reasons, the reactive power control and the active power curtailment in an attempt to manage the voltage and/or thermal constraints may not be necessary in every case. Implementing the control actions that are only necessary can potentially reduce the reactive power requirement for voltage control and the power loss in the curtailment process, allowing more power exports as a consequence.

In doing so, the joint V&T Mgt scheme requires a strategy to match the control actions to the severity of the voltage and line capacity situations. Such an approach, termed ‘Operational Windows’ (OW) enhances the joint V&T Mgt and is detailed in Chapter 5.

The main aspects of the decentralised V&T Mgt scheme as well as the core algorithms evolving reactive power control, active power curtailment, sensitivity analyses and reduction rate are significant contributions to knowledge. These are the basis of several academic papers including [79, 80, 121, 122].

# Chapter 5

# Operational Windows Approach for Joint Decentralised Voltage and Thermal Management

## 5.1 Introduction

This chapter explains the control methodology for enhanced decentralised voltage and thermal management, termed ‘Operational Windows’ (OW). Considering that DG developers will require the highest possible energy exports and DNOs might tolerate short-term, low-impact voltage and thermal breaches, the settings of the actual control mechanism (e.g., thresholds, target values and holding time) require special attention. In this chapter, the concept of operational windows related to time and severity is developed to capture the constrained situations as in the previous schemes such severity and breaches on this basis are not allowed. In the case study, operation of the approach implemented on a 3-bus radial feeder is demonstrated and fine tuning of different control settings is compared in order to assess the technical and economic trade-offs. The work presented here is mainly contributed from one of the author’s publications in [77].

## 5.2 Operational Windows Approach

The operational windows approach extends the joint voltage and thermal management with the sensitivity analysis method. It is used to capture the voltage or thermal variations that arise in a range from lesser to very severe situations and to implement appropriate control actions. The operational windows concept uses monitoring of conditions over a continuous fixed sampling period to characterise the behaviour of voltage and line power flow variations and determine the appropriate control response. Here it consists of five windows (1 to 5) reflecting the behaviour of voltage and power flows due to wind and demand characteristics. Each window is specifically defined by a mechanism that involves two thresholds, a target and a holding time value. The thresholds – threshold-one and threshold-two – and the target value are set with respect to the statutory voltage limit or line capacity. Threshold-one and threshold-two are set below and above the limit, respectively (details are provided in Section 5.2). These window settings are tuneable and are the key element for capturing the constrained situations and validating the most effective control actions to be implemented. Definition of each window and the control action that is assigned to the windows are provided in Table 5 - 1. The operation for each window and the corresponding control actions are explained as follows:

**Table 5 - 1: Definitions and control actions of Operational Windows strategy**

| Windows | Names | Definitions | Control |
|---|---|---|---|
| **Window 1 (W1)** | Normal Operation | • Constraint is below Threshold-one (Th-one) | No action |
| **Window 2 (W2)** | On-hold | • Exceeding Th-one but below Threshold-two (Th-two)<br>• Less than holding time | No action (on-hold) |
| **Window 3 (W3)** | Severe and Extended | • Exceeding Th-One and Th-Two<br>• Less than holding time | V&T Mgt |
| **Window 4 (W4)** | Breach and Extended | • Exceeding Th-One but below Th-Two<br>• Longer than holding time | V&T Mgt |
| **Window 5 (W5)** | Severe and Extended (Worst case) | • Exceeding Th-One and Th-Two<br>• Longer than holding time | V&T Mgt |

Window 1: Normal Operation

Voltage or line flow is below the threshold values and therefore no action is required.

Window 2: On-hold

When voltage (or line flows) exceeds threshold-one (set slightly below the limit to define the severity), the scheme waits until a holding time is up without performing any action. After the holding time ends, three possibilities exist. If the situation returns to normal (window 1), no further action is required. If the measured parameter continues but is below threshold-two, the situation would fall into Window 4 and the holding time restarts. If the measured parameter breaches threshold-two, the situation will be replaced either by Windows 3 or 5 and the holding time restarts.

Window 3: Severe and Sudden

Continuing from Window 2, the measured parameter breaches threshold-one and threshold-two. Although the breaching occurrence is less than the holding time, control action is immediate to ensure security of the network.

Window 4: Breach and Extended

This stage occurs when the measured parameter exceeds the threshold-one for longer than the holding time. This could affect performance of network infrastructure or the situation could be worsened due to other conditions, e.g., a close-by wind farm producing more power.

Window 5: Severe and Extended

The last stage is the worst case that may occur. The measured parameter breaches threshold-two for longer than the holding time, prompting immediate action.

As these five severity windows are applied on the same basis to the voltage and thermal constraints, the probability of occurrence of the voltage rise and thermal overload situations at each time step therefore becomes 25 possible situations, i.e., 5 windows for voltage × 5 windows for thermal = 25 possible situations

This probability of occurrence covers the full range of severity. The voltage and thermal constraints are continuously mapped against these windows. For a single constraint, the V Mgt or T Mgt is directly applied. A severe situation when two constraint breaches occur requires a validation of final control action in which the priority is given to the T Mgt, i.e., whenever window 3, 4 or 5 for T Mgt is activated, its action will remain until normal operation (without the constraints) of the DG unit can be adopted. Validation of the final control action follows the priority rule as shown in Table 5 - 2. The OW decision table covers all 25 severity situations and provides the final control command for the V&T Mgt full approach. Validation of how the operational windows can be used to capture the severity of the voltage and line overload problems is presented in Section 5.3.

**Table 5 - 2: Operational windows priority rule table (W1 = Window 1)**

<table>
<tr><th>V Mgt →<br>T Mgt ↓</th><th>W1</th><th>W2</th><th>W3</th><th>W4</th><th>W5</th></tr>
<tr><td>W1</td><td>None</td><td>None<br>(V Mgt on hold)</td><td colspan="3" rowspan="2">V Mgt</td></tr>
<tr><td>W2</td><td>None<br>(T Mgt on hold)</td><td>None<br>(V&T Mgt on hold)</td></tr>
<tr><td>W3</td><td colspan="2" rowspan="3">T Mgt</td><td colspan="3" rowspan="3">T Mgt<br>Then<br>V Mgt</td></tr>
<tr><td>W4</td></tr>
<tr><td>W5</td></tr>
</table>

## 5.3 Tuneable Settings: Threshold, Target and Holding Time Values

The arrangement of the threshold and target values is depicted in Figure 5 - 1. The threshold values are used to define the degree of severity of voltage rise or overload and determine whether the control actions are required. The target value is used as a safe level to estimate the reactive or real power set point required by the corresponding control scheme. Threshold-one is the first level to ensure the scheme activation and is set lower than the maximum limit. If the constraint exceeds threshold-one for a short time (less than the holding time), the corresponding scheme is activated. Threshold-two, set above the maximum statutory/rating level, is the point where the constraint is defined severe with immediate control action implemented. The target value is set below threshold-one (and therefore below the limit) as a conservative, restricted level. The holding time is used to validate the control actions and is set based on assumed frequency of occurrence of the generation variations (e.g., wind peak over time) and time delays or response times of other regulating devices identified in the network. The five windows reflecting the severity of occurrence are specified based on the threshold-one, threshold-two and holding time values. The OW strategy provides effective capture of the constraint variations and allows for fine tuning of the appropriate control scheme.

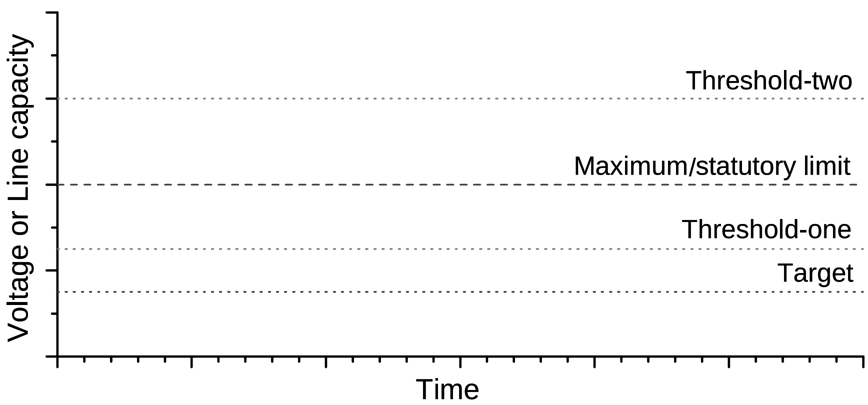



**Figure 5 - 1: Arrangement of the threshold and target values**

The threshold, target and holding time values are particularly useful in the context of variable generation, e.g., wind, where fluctuations over a short period are frequent. Therefore, these fixed settings can prevent an excessive number of control actions as wind varies. These values are also tuneable to allow precise control actions against the occurrence of constraints in different network, load and generation characteristics. It is conceivable that they could be combined with an auto-adaptive learning mechanism that continuously updates the settings.

A summary of the control settings for the V&T Mgt scheme adopting the OW approach is shown in Table 5 - 3. The operational windows settings are added to the V&T Mgt schemes based-on the reduction rate method and the sensitivity analysis as presented in Table 4 - 3 in Chapter 4.

**Table 5 - 3: Summary of the V&T Mgt and OW control settings requirement**

| Schemes | V-Mgt | | T-Mgt |
|---|---|---|---|
| **Methods** | **Reactive power control** | **Active power curtailment** | **Active power curtailment** |
| **Reduction Rate** | • Step-wise PF<br>• Q capability<br>• V threshold<br>• V target | • % trim<br>• V threshold<br>• Time delay | • % trim<br>• S threshold<br>• Time delay |
| **Sensitivity Analysis** | • $\partial V/\partial Q$<br>• Q capability<br>• V threshold<br>• V target | • $\partial V/\partial P$<br>• V threshold<br>• V target | • $\partial S/\partial P$<br>• S threshold<br>• S target |
| **Operational Windows Approach** | • $\partial V/\partial Q$<br>• Q capability<br>• Holding time | • $\partial V/\partial P$<br>• Holding time | • $\partial S/\partial P$<br>• Holding time |
| | • V threshold-two<br>• V upper limit<br>• V threshold-one<br>• V target | • V threshold-two<br>• V upper limit<br>• V threshold-one<br>• V target | • S threshold-two<br>• S maximum limit<br>• S threshold-one<br>• S target |

## 5.4 Validation of Scheme

The control actions of the operational windows voltage and thermal management are presented in this section. The case study and performance assessment are carried out using the same 3-bus test feeder used in Chapter 4 (Figure 4 - 11) with a CHP unit and a 6-MW wind farm on a 60-minute time-period simulation. Again, the wind farm operates at unity power factor but has capability for 0.95 inductive/capacitive power factors. Demand is held at a constant minimum level of 40% of peak. The wind generation profile shown in Figure 4 - 16 is applied.

The preset values for threshold-one, threshold-two, target and time delay for voltage and line flows are shown in Table 5 - 4. These were defined after initial experiment action but a thorough examination of the setting and their influence on performance is given later. As depicted in the time series in Figure 5 - 2, the 6-MW wind farm drives the voltage to rise above threshold-one for most of the time. Based on the preset settings, the operational windows corresponding to the voltage and thermal constraints can be characterised. Given the 5-minute holding time, window 2 (the beginning to 4$^{th}$ minute), 4 (the 5$^{th}$ to 14$^{th}$ minute), 3 (the 17$^{th}$ to 33$^{rd}$ minute) and 5 (around the 42$^{nd}$ to 60$^{th}$ minute) shown in the figure are then identified to assist the voltage management scheme. Window 5 expects immediate voltage control action as the voltage breaches threshold-two over a longer period.

**Table 5 - 4: Settings for operational windows**

| Settings | Voltage | Line flows |
|---|---|---|
| **Threshold-one** | 1.0585pu<br>(0.15% below nominal V limit) | 4.5% below maximum capacity |
| **Threshold-two** | 1.062pu<br>(0.2% above nominal V limit) | 3% above maximum capacity |
| **Target** | 1.0575pu<br>(0.25% below nominal V limit) | 5% below maximum capacity |
| **Time delay** | 5 minutes | 5 minutes |

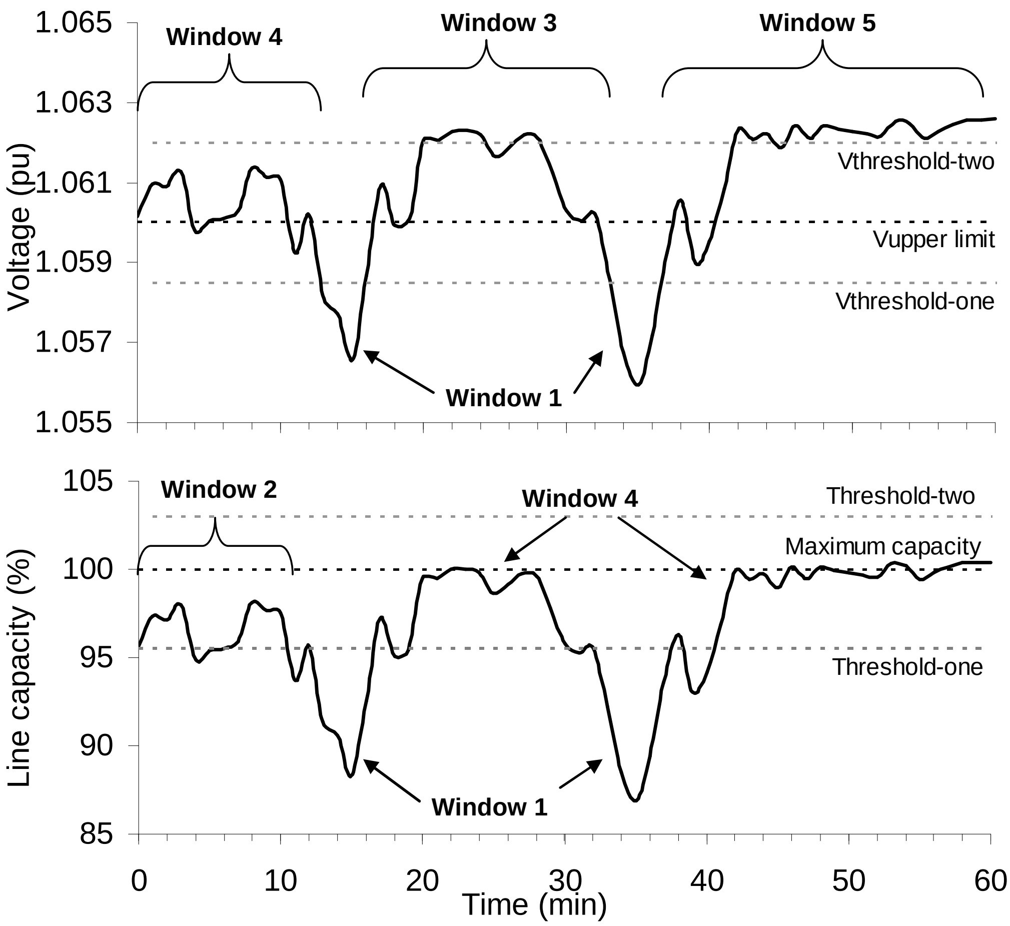



**Figure 5 - 2: (Top) voltage at bus 3 and (bottom) line flows constraints and the identified operational windows for 6-MW wind farm**

On the other hand, the line flows exceeds threshold-one but remain below threshold-two. Therefore, no action is required until around the 20$^{th}$ minute. Around the 42$^{nd}$ minute (with the wind farm being operated normally), the line flows tends to exceed threshold-one for an extended period and control actions follow.

According to the characterised operational windows, the relevant control actions are then validated and promptly applied. The identified windows and the voltage profile at bus 3 for the cases without control and with voltage and thermal management are shown in Figure 5 - 3. The shaded area shows when voltage and thermal management control is immediate, i.e., windows 3 to 5 (see Table 5 - 2). From the beginning to the 4$^{th}$ minute (the first five minutes equal to the holding time), no action is required as the V&T Mgt is on-hold (voltage constraint is defined by window 2). After the holding time is up, i.e. the 5$^{th}$ to 6$^{th}$ minute, the voltage constraint is defined as window 4 as the voltage now exceeds threshold-one for longer than the 5-minute holding time. The thermal constraint is in windows 1 and 2, as can be observed in Figure 5 - 4. The V Mgt then reacts to request wind farm reactive power control to maintain the voltage at the target. Similar actions also occur at the 21$^{st}$ and 42$^{nd}$ to 44$^{th}$ minutes.

Figure 5 - 4 shows power flows on the line between buses 2-3 and the thermal management remains on-hold for most of the time (window 2) except for the 10$^{th}$, 24$^{th}$ to 25$^{th}$ and 46$^{th}$ to 48$^{th}$ minutes where the constraint is identified as window 4. The thermal management (as the first priority) reacts to curtail the wind power output to relieve the overloaded line. This effect is also seen on the voltage profile as a duplicate trace during the 25-30$^{th}$ and the 46-60$^{th}$ minutes (when the T Mgt was triggered by window 4 and the V Mgt was indirectly disabled). A small increase in the line flows during the 7$^{th}$ and 22$^{nd}$ minutes is due to the reactive power flow by the activation of the voltage management.

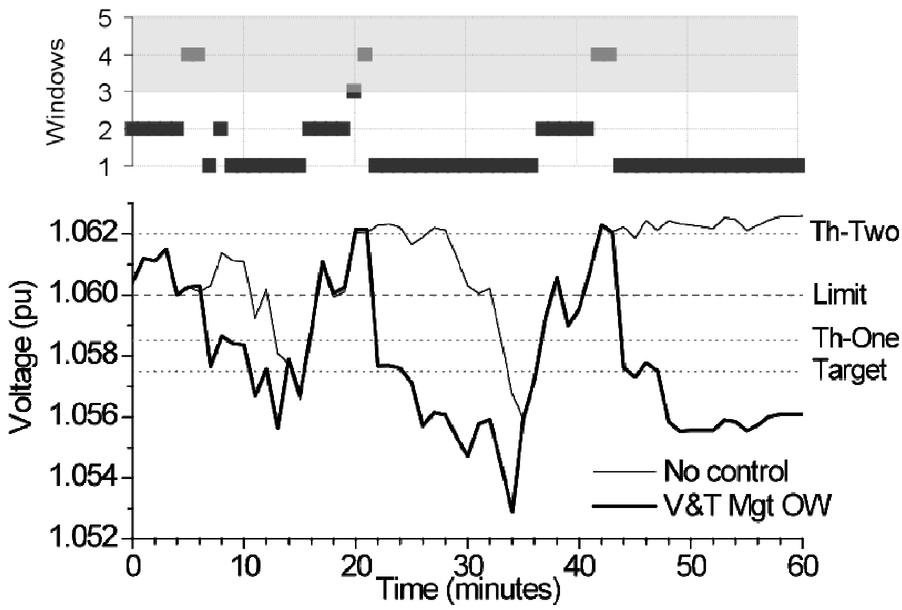



**Figure 5 - 3: (Top) identified windows and (bottom) voltage at bus 3 without control and with the decentralised V&T Mgt OW**

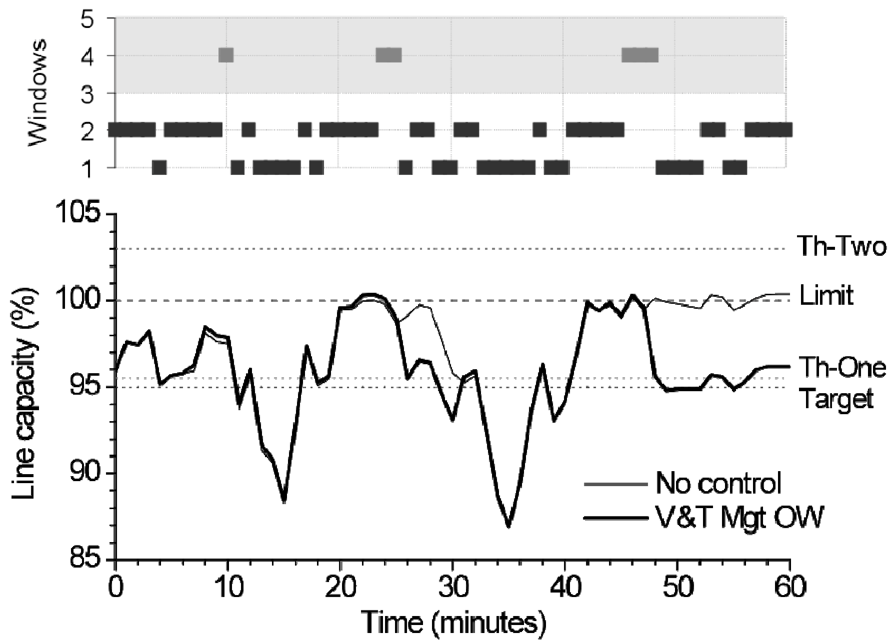



**Figure 5 - 4: (Top) identified windows and (bottom) line flows without control and with the decentralised V&T Mgt OW**

## 5.5 Case Study for Different Selected Tuned Settings and Performance Assessment

Performance of the operational windows V&T Mgt scheme relies on the values chosen for the settings described in Section 5.3. Here, 3 scenarios comprising a total of 9 cases (including the case in the previous section) are used to test different window settings that reflect different constraint possibilities. The scenarios comprise three different settings of the two thresholds in relation to the statutory or asset limits; these are: 'Narrow', 'Normal' and 'Wide' as shown in Table 5 - 5. Narrow has two thresholds that are closer to the limits, Wide indicates a broader span and Normal is used in Section 5.3. For each scenario, three values of holding time are applied: 2, 5 and 15 minutes. On this basis, for instance, the analysis in Section 5.4 is indicated by Normal-5.

**Table 5 - 5: Selected tuned settings (based on the statutory limits: 1.06pu voltage and 100% line capacity)**

| Voltage | Threshold-one | Threshold-two |
|---|---|---|
| Narrow | 1.059 | 1.061 |
| Normal | 1.0585 | 1.062 |
| Wide | 1.058 | 1.065 |
| Line flows | Threshold-one | Threshold-two |
| Narrow | 98% | 102% |
| Normal | 95.5% | 103% |
| Wide | 95.5% | 105% |

In order to appraise the trade-offs between the technical and economic benefits of each case the performance evaluation was carried out using the 3-bus system. As illustrated in Figure 5 - 5, the technical performance was evaluated against the periods that constraints exceed the limits of 1.06pu voltage and 100% line capacity, over a one-hour simulation period. It should be noted that the 6-MW 'no control' case would never be achieved due to the constraints but is presented here for comparison.

With regards to maintaining voltage below limits the Narrow scenario shows the most effective performance as the threshold values create a more rigid arrangement closer to the limits. Extending the holding time setting (a more relaxed arrangement) would cause the voltage to rise above the limit for longer before the scheme takes action. On the other hand, for power flow management, the Normal and Wide scenarios show better performance on the same holding time basis (2 and 5 minutes) despite an improvement from applying the Wide scenario on the 15-minute holding time. This is due to quicker activation of the scheme as threshold-one is set farther below the limit. Comparing the same scenarios, however, the results give similar levels of voltage management. The 15-minute holding time cases demonstrate poorer performance whereas the shorter holding time cases are able to better overcome the line power flow constraint. The operational windows scheme is able to reduce the severity of voltage rise and line overload compared to the 6-MW without control for all cases except the Narrow and Normal scenarios with 15-minute holding time for mitigating the line overload due to the activation of the voltage management that increases the reactive power flow in line (as shown in the validation).

The economic benefit for each case is evaluated and compared in terms of extra energy exports, the ratio of the energy lost in the generation curtailment to the energy export (as shown in Figure 5 - 6), the wind capacity factor and the revenues made by the generation, assuming an energy price of £40/MWh [95] (as presented in Table 5 - 6). Although the economic assessment is based on a one-hour analysis in this study, the results provide an indicative view of the performance of the proposed scheme. The energy export increases when setting the holding time longer. This allows the wind farm to continuously generate power output before the holding time ends. As a consequence, more production revenues can be made and the amount of the curtailed power output is reduced. This can also be verified by an improvement in the capacity factors within the same scenario. The Narrow scenario presents slightly more energy export as threshold-one is set closer to the limit (slower activation). Likewise, the amount of energy curtailed when setting the thresholds closer to the limit is the smallest amongst the three scenarios. The highest revenue and the largest capacity factor were achieved when adopting the Narrow scenario at 15-minute holding time. This scenario gives approximately 20% higher revenue than that obtained by the fit-and-forget approach.

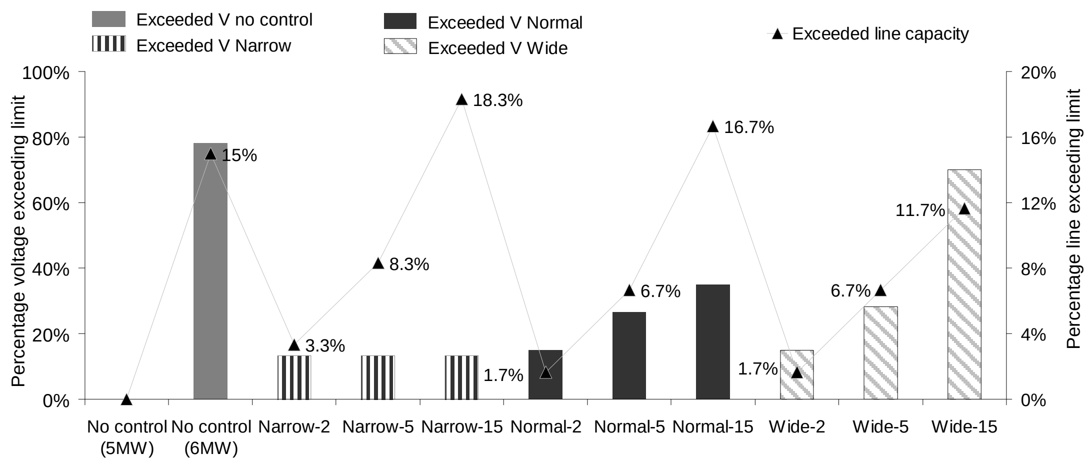



**Figure 5 - 5: Performance comparison based on the periods of voltage exceeding the 1.06pu limit (%) and of line flows exceeding capacity limit (%)**

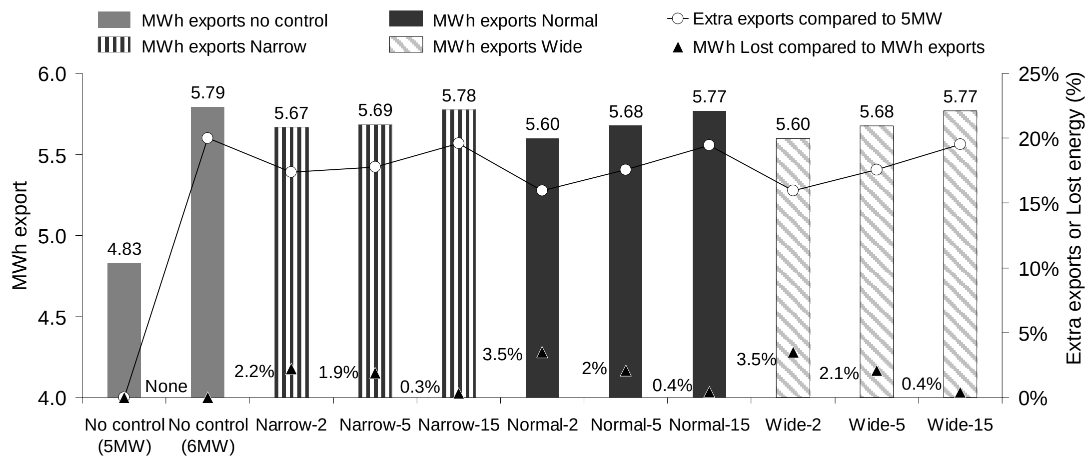



**Figure 5 - 6: Performance comparison based on power export (MWh); extra export compared to a 5MW wind capacity (%) and power lost compared to power export (%)**

**Table 5 - 6: Production revenues and wind capacity factors for different cases (hour-long simulation period)**

| Cases | No control (5MW) | No control (6MW) | Narrow-2 | Narrow-5 | Narrow-15 |
|---|---|---|---|---|---|
| Capacity Factor | 0.966 | 0.966 | 0.945 | 0.948 | 0.963 |
| Revenue (£) | 193.12 | 231.74 | 226.71 | 227.46 | 231.01 |

| Cases | Normal-2 | Normal-5 | Normal-15 | Wide-2 | Wide-5 | Wide-15 |
|---|---|---|---|---|---|---|
| Capacity Factor | 0.933 | 0.946 | 0.961 | 0.933 | 0.946 | 0.962 |
| Revenue (£) | 223.92 | 227.05 | 230.72 | 223.92 | 227.05 | 230.82 |

As demonstrated, the economic benefit of extra energy export could be achieved with a longer holding time and the setting of threshold-one closer to the limit. These scenarios however are more prone to raising stress on the system performance. This presents a trade-off between obtaining extra power generation while having to tolerate less severe constraints. As a consequence, such a compromise framework will need to be made between the DNOs and the wind farm developers if the techno-economic benefits of the operational windows scheme are to be seen directly. Alternatively the voltage and flow settings may be revised downwards such that excursions above limits are less likely.

## 5.6 Chapter Five Summary

This chapter introduced a decentralised control for synchronised management of voltage rise and line thermal constraints based on an operational windows approach. The scheme adopts the capabilities of DG in providing reactive power control and generation curtailment based on sensitivity analysis (as presented in Chapter 4) to locally overcome constraints close to the DG connection location. The operational windows concept can effectively capture more or less severe situations where voltage and/or line thermal flows exceed the statutory or rating limits. Different settings of the corresponding thresholds and the operational windows have been demonstrated and discussed with regard to technical and economic trade-offs. Depending upon the DNOs requirements, the more relaxed scenarios for the voltage statutory limitation and the power carrying capability of line would enable the economic benefits to be gained without severely exceeding the constraints.

# Chapter 6

# Coordinated and Centralised Voltage and Thermal Constraint Management

## 6.1 Introduction

The performance of decentralised schemes to locally manage voltage rise and thermal overload using the active and reactive power capability of DG has been presented in the previous chapters. The schemes used only information available at the DG connection and ignored advances in coordination and communication. Some limitations in their management capability were identified. While the decentralised control can effectively provide local constraint management, in a centralised aspect its capability may be limited. With distribution networks that involve more complexity and diversity, coordination, communication and optimisation tools will be required to support the active network management development. With a large volume of active management research and development, there are few answers to the necessary extent of coordination, communication and optimisation solutions required for active network management and what the associated benefits and risks of those approaches will be. This chapter attempts to shed some light on these issues by extending the decentralised management schemes and investigating the effect of increasing coordination, communication and optimisation on the active management schemes.

As presented in Chapter 3, three approaches along the active management spectrum that were used to classify innovative network control mechanisms: decentralised, coordinated and centralised. To allow comparison with the developed decentralised schemes this chapter develops two new active management schemes that are based on the coordinated and centralised approaches by assuming that associated communication tools are available. The two management schemes are:

- Joint voltage and thermal management coordinated with OLTC transformer actions using a request signal method;

- Centralised optimal power flow for voltage and thermal management using active and reactive power constraints and OLTC tap action.

In each scheme, the control methodology and the validation in a test feeder are presented. Case studies depicting the control function of each scheme are investigated. Overall performance comparisons between the decentralised schemes and those developed in this chapter are assessed on the basis of control performance, wind penetration level, system losses, reactive power exchanges and risk-benefit identification. Detailed economic viability evaluation is also presented.

## 6.2 Coordinated Voltage and Thermal Management

Prior to developing the decentralised joint management scheme (in Chapter 4 and 5), the author had investigated the effectiveness of employing reactive power control for decentralised voltage management alone in a semi-coordinated manner using OLTC voltage regulation but without communication between them [121]. Instead, it uses a time delay mechanism from the OLTC operation to define the reactive power control action that manages voltage locally. The OLTC uses a similar control mechanism to line rise compensation but with a time delay being assigned for each tap action. This delay is assumed known to DG units nearby employing the decentralised voltage control scheme. In this way, the DG and the OLTC could coordinate without communication required. With the later work on the sensitivity analysis and multiple constraints, the semi-coordinated scheme was improved using a different method that allows the schemes to cope with voltage rise and line overload simultaneously in real-time as will be presented. However, more details of the semi-coordination scheme can be found in the publication [121] in the Appendix.

In this section, the capability of coordinating the OLTC voltage regulation is further developed and investigated. The technique assists with decentralised voltage control when the DG reactive power capability is reached by requesting a tap action from an

OLTC transformer. This is intended as an alternative to active power curtailment in order to maximise power export. This method extends the degree of coordination from the earlier work [121] for the reason that relying only on the tapping time delay for the DG to coordinate its voltage control action after the OLTC may be ineffective to cope with the voltage problems in more severe situations (e.g., larger network and more variable DG units) compared to using direct communication. Here, it is also assumed that two-way communication is in place to allow the OLTC and the DG to assist each other in mitigating the voltage problem and facilitate remote monitoring of the actions.

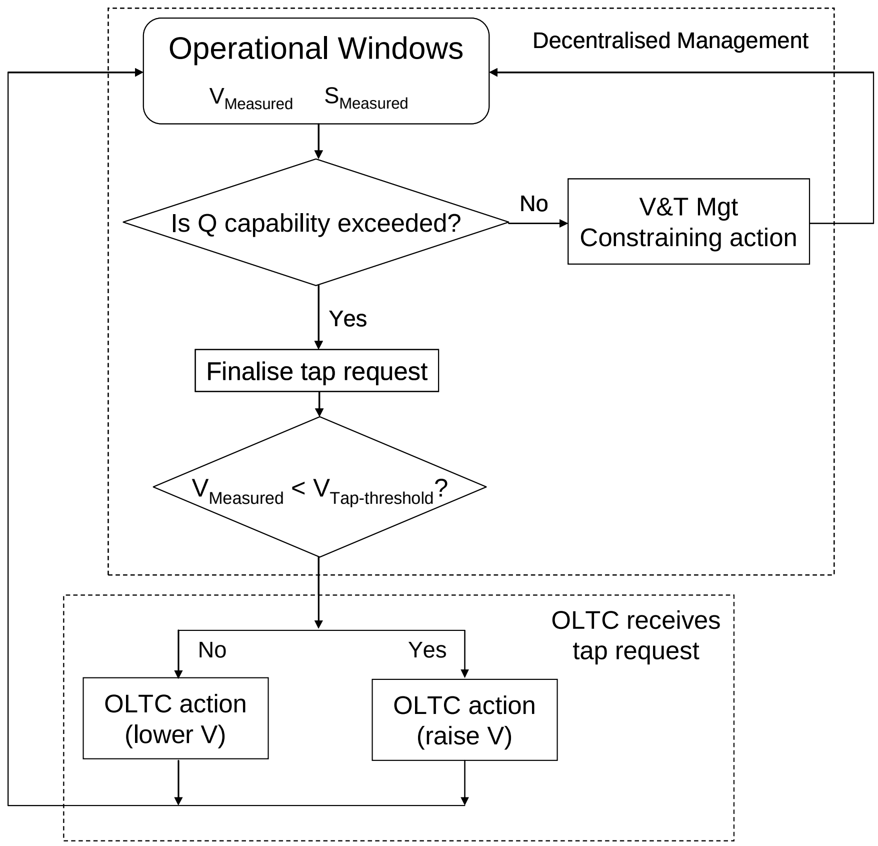



**Figure 6 - 1: Functional diagram of the coordinated voltage and thermal management**

A functional diagram of the coordinated voltage and thermal management is illustrated in Figure 6 - 1. At each time step, the operational windows approach (presented in Chapter 5) identifies the constraint situation and dictate the corresponding control scheme - this is referred to as stage 1. The joint decentralised voltage and thermal management scheme based on the sensitivity analysis and without demand and generation forecast is employed. If no constraints are detected, the DG will continue its normal operation. If the local, corrective control (constraining) actions are required, the joint management scheme will take its action to deal with the constraints first.

For the OLTC, it operates based on a tap request being sent from the DG where only one tap change per request will be granted. The reason for this is to avoid excessive voltage change in the rest of the network due to the relatively wide tap step of typical transformers. In addition, as the tap change of the transformer will affect the whole voltage profile in the network the attempt to bring voltage down may cause voltage drops particularly in areas where demand is high. To avoid excessive voltage drops, a lower voltage threshold ($V_{Tap\text{-}threshold}$) is applied at the DG bus in order to prevent the OLTC from reducing the voltage further. In this study, a $V_{Tap\text{-}threshold}$ value of 1pu is set as a safe level assuming that voltages in the remaining part of the network would drop below the statutory limit if by the tap action the voltage at the target bus is fixed lower than this threshold (1pu).

After the corrective control actions of the decentralised scheme have been taken, the power factor of DG will be constantly checked against the reactive power capability limit. The DG voltage is also checked against $V_{Tap\text{-}threshold}$. If capability is reached a ‘request’ signal will be finalised and sent to the OLTC transformer to perform a tap step change in order to bring down or raise the voltage. After the OLTC tap action has taken place, the operational windows decentralised scheme continues to monitor the constraints (returns to stage 1).

The $V_{Tap\text{-}threshold}$ value can be determined by evaluating the maximum and minimum voltage sensitivities relative to a change in the target bus voltage. In case a line overload problem occurs, the thermal management scheme using active power curtailment based on the sensitivity analysis is applied. During the thermal management process, all settings for the voltage control will remain unchanged at their prior settings.

### 6.2.1 Validation of Scheme

The coordinated OLTC action is demonstrated in this subsection. The extension of the joint voltage and thermal management is based on additional voltage regulation provided by OLTC transformer therefore the effect will be clearly seen with voltage management. The validation first of all takes a close look at voltage management assuming that the line overload is ignored. The operation of the previously uncoordinated decentralised voltage and thermal management schemes is compared. The validations are carried out in the 3-bus test feeder as previously used in Chapter 4 (Figure 4 - 11). The one-minute demand and wind profiles over one hour are applied (Figure 4 - 16).

*Coordinated Voltage Management*

For voltage management alone, three voltage management schemes are compared in Figure 6 - 2: the decentralised voltage management scheme, the operational windows decentralised voltage and thermal management and the coordinated voltage management. The first two schemes assume the reactive power capability of the wind farm at 0.95 inductive/capacitive (their control behaviours are presented here only for comparison). For the coordinated scheme, the power factor at unity and a range of 0.98 inductive/capacitive is applied. The reason for applying a narrower reactive power capability is to force the OLTC to take action as otherwise the voltage rise would be managed solely within the DG 0.95 power factor range which is sufficient to manage the voltage rise here.

It can be seen that for all schemes, when the wind farm's reactive power capability is available it is adequate to overcome the voltage rise and that voltage support from the OLTC transformer is not necessary. The decentralised V Mgt scheme performs effectively in managing the voltage rise as it focuses on the voltage impact alone whereas the operational windows scheme results in minor short periods of voltage rise due to the holding time function (see Chapter 5). The coordinated OLTC scheme operates similarly to the operational windows scheme except in minutes 12 to 14, 26 to 30, 34 and 48 to 60 due to the effect of the thermal management. The tap request is also not required as the power factor range of 0.98 is sufficient to manage the voltage rise in this case. To demonstrate the advantage of coordinating the tap operation, here the coordinated OLTC scheme when the wind farm is fixed at unity power shows a different outcome.

The performance of voltage management coordinated OLTC with the wind farm operating at 0.98 and unity power factor are analysed further in Figure 6 - 3. It is clearly seen that after the 5 minute holding time of the operational windows is up, the unity power factor wind farm requests a tap action as it is not able to manage the voltage rise (minutes 6 to 15, 22 to 36 and 44 to 60, (Figure 6 - 3 (middle)). Consequently, the OLTC transformer steps one tap up (Figure 6 - 3 (bottom)) to bring the voltage down and the wind farm continues to operate normally as the drop in voltage adds extra headroom for voltage variations for the remaining periods. This shows that the coordinated tap action can significantly provide extra voltage headroom to the network and is effective for voltage management. However, as the tap operation of a transformer can affect the network voltage and power flows as a whole, in a larger network it is necessary to ensure that such a tap request will not cause additional voltage problems elsewhere. The validation is carried out in a 3-bus feeder therefore the tap change action will only affect the wind farm site.

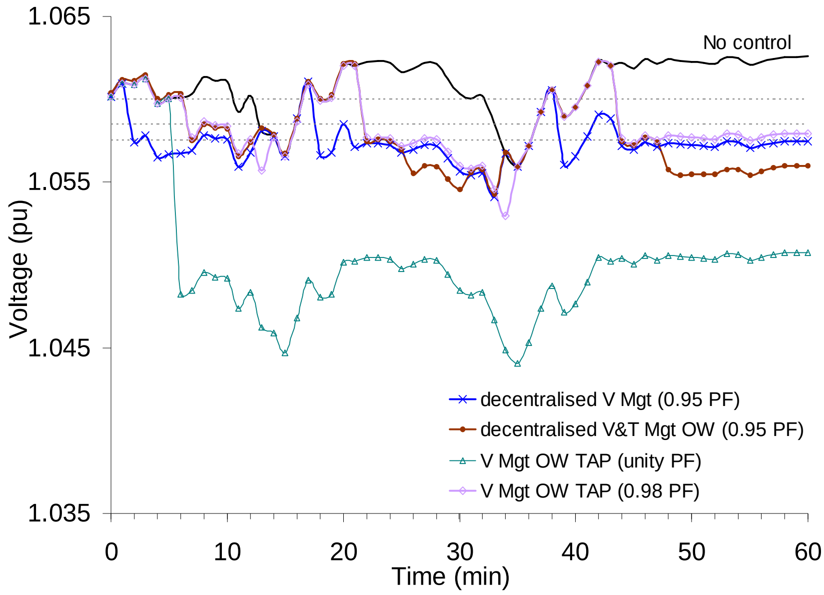



**Figure 6 - 2: Comparison of voltage profiles for the decentralised voltage management (V Mgt); the joint management operational windows (V&T Mgt OW) and the voltage management coordinated OLTC at unity and 0.98 power factor (V&T Mgt OW TAP)**

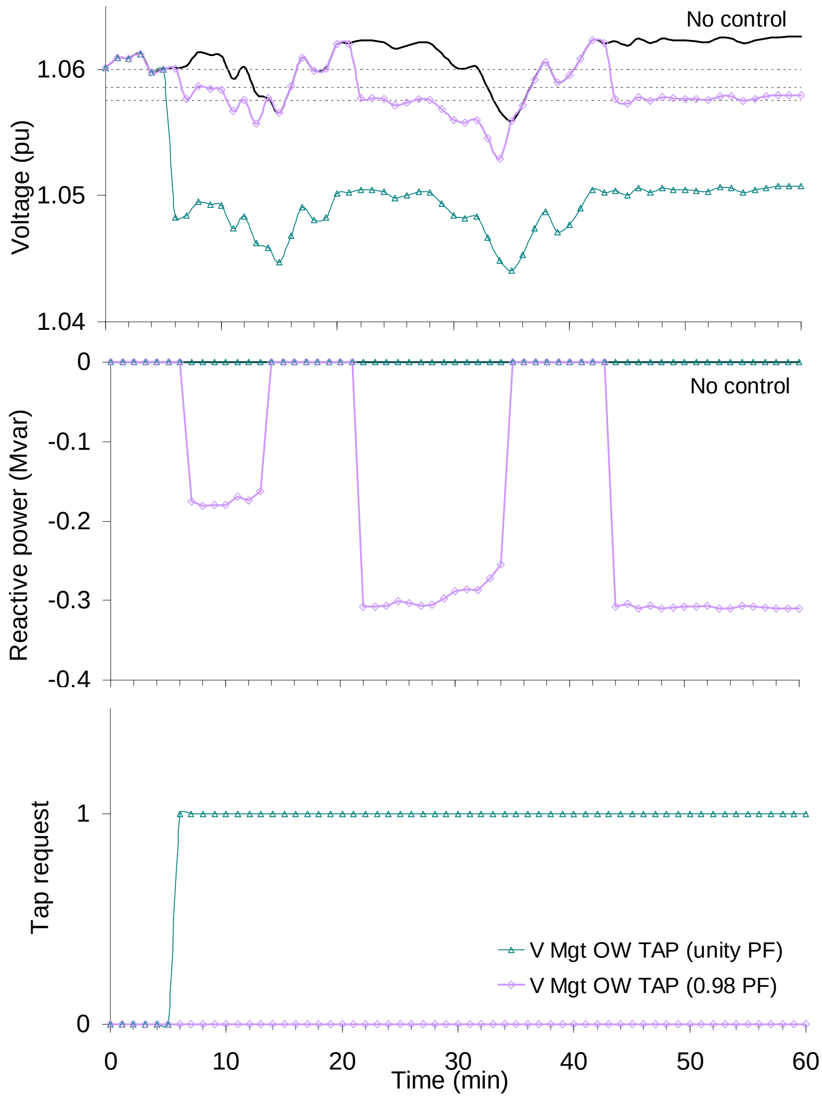



**Figure 6 - 3: (Top) voltage profiles, (middle) reactive power and (bottom) tap request for the centralised voltage management coordinated OLTC transformer (V Mgt OW TAP) at unity and 0.98 power factors**

*Joint Voltage and Thermal Management Coordinated OLTC*

As demonstrated previously, the effect of the tap operation was only seen (in this analysis) when the wind farm was fixed to operate at unity power factor. The study was repeated for a power factor range of 0.99 for the coordinated OLTC scheme that included line overload management (the joint management coordinated OLTC scheme). The voltage profile was also similar to the 0.98 power factor case as a result of having sufficient reactive power capability as well as action from the active power curtailment. According to the result, it can be implied that with the DG being able to manage the voltage problem locally, the requirement for OLTC tap action can be reduced. To investigate the control performance of the joint management coordinated OLTC scheme further, the analysis has repeated with increasing wind penetration in order to identify the capability break-point of the voltage and thermal management coordinated OLTC, i.e., where it fails. The studies for 6, 8, 10 and 12-MW farms were conducted for the same 0.99 power factor range. The results based on energy export, system energy losses, wind capacity factor and overvoltage and overload durations are compared in Table 6 - 1. As expected, the increase in wind penetration reduces the capability of the scheme to manage both constraints, i.e., longer periods of voltage and line loading exceeding the limits are observed. The capacity factor that dictates the actual wind power exports is also decreased. Again with the effect of active power curtailment following the overload problem as the first priority to be activated, the tap requests are not present.

All cases result in the overvoltage and line overload which can dictate an increase in the level of the capacity break-point. In practice, the network capability to withstand voltage rise and line overload may be defined. For instance, if 30% and 15% durations of overvoltage and line overload over time (in this case one hour) were allowed by DNOs the 8-MW wind farm would be a critical capacity to be connected when the coordinated voltage and thermal management was employed.

**Table 6 - 1: Performance comparisons of the centralised voltage and thermal management at 6, 8, 10, and 12-MW wind unit at 0.99 power factor limit (hour-long simulation period)**

| V&T Mgt OW TAP (0.99 PF) | Energy export (MWh) | Energy loss (MWh) | Capacity factor | Voltage duration exceeding 1.06pu | Line overload duration exceeding 100% |
|---|---|---|---|---|---|
| 6-MW | 5.68 | 0.47 | 0.95 | 23.3% | 5% |
| 8-MW | 5.74 | 0.48 | 0.72 | 31.67% | 16.67% |
| 10-MW | 5.84 | 0.49 | 0.58 | 35% | 16.67% |
| 12-MW | 5.89 | 0.50 | 0.49 | 33.3% | 18.3% |

## 6.3 Centralised Optimal Power Flow for Joint Voltage and Thermal Management

In this section, a fully centralised, optimised environment with full-scale measurement and communication is examined. Here, an optimal power flow (OPF) tool integrated in PSS/E to provide optimal operation for voltage rise and line overload constraint management is employed.

Optimal Power Flow is an optimisation tool used to solve complex power flow problems. The solution is derived from one or more objectives to be attained under predefined constraints in combination. OPF was developed to find an optimal dispatch of generation taking into account line flow limits in order to minimise fuel costs [123], termed ‘economic dispatch’. In addition, OPF can be used to solve voltage-reactive power dispatch and contingency-security constraints amongst several objectives, e.g., minimisation of losses, deviations, violations and load shedding [123]. In the literature, OPF is employed to evaluate the available headroom in a distribution network to accommodate new DG with respect to voltage and line thermal limits [124, 125]. Boehme *et al.* [18] developed time sequential OPF for multiple DG sites to evaluate the maximum energy extracted where generation curtailment is used to satisfy the network voltage and thermal limits. In [126], OPF is employed to perform reactive power reserves management where the reactive reserve of generators is maximised in order to improve the voltage stability margin within critical areas in a network and to support system voltages under disturbances or increased load. With the prospect of providing smart grid based solutions however the OPF features have not extensively been utilised. Only a few developments of OPF for actual smart grids operation are presented in recent research. A Genetic Algorithm-based technique is applied to solve three-phase distribution optimal power flow problem to reduce the computational burden in real-time applications [127]. An OPF based on a multi-period scenario developed in [128] determines optimal sites and capacity of renewable DG units that minimise energy losses. In an active radial network with large-volume DG integration, optimal power flow management based on a ‘cost-scaling push-relabel’ algorithm for a multi-agent system is developed to enhance the computational efforts of solving power flow problems and reduce the number of messages exchanged by localised control agents [129].

This section extends the OPF previous work in [18] (carried out at the University of Edinburgh) where the OPF is applied to time series of multiple DG units to estimate the maximum energy export by employing generation curtailment using pseudo-economic dispatch within the voltage and thermal constraints. For the optimisation, the DG units are fixed to operate at unity power factor, i.e., the reactive power capability is not taken into account, and the secondary voltage of the transformer is set to a fixed value (i.e. 1pu). However, the work presents some limitations in the actual and available control capability that the DG unit and the OLTC voltage regulation can deliver. In this research, the OPF tool is used with a similar objective but in a different aspect from the previous work in that those limitations will be fully optimised. Also, the previous OPF process and analysis were automated in PSS/E and scripted in IPLAN programming language.

Here, the OPF tool integrated in PSS/E software and interfaced with Python is used to perform a multi-constraint and multi-objective optimisation for real-time voltage and thermal (power flow) management and to maximise wind generation export. The OPF voltage and thermal management scheme allows optimisation within predefined ranges of the DG unit's reactive power capability and OLTC transformer secondary voltage while maximising energy export and maintaining the constraints. The aim is to investigate the capability and limitation of introducing an optimisation tool as a smart grid based solution and compare with the other schemes previously developed in this research. Features of the PSS/E OPF tool interfaced with Python, methodology and case investigations of the OPF-based voltage and thermal management scheme are presented in this section. Case studies of the scheme will be presented and analysed later.

### 6.3.1 Optimal Power Flow in PSS/E

In most power system software including PSS/E, OPF is available as a built-in (or add-on) application alongside normal power flow. In PSS/E, the OPF tool is an integrated application consisting of a set of functions for users to choose the desired objective and constraint formulations [117]. Features of the OPF tool in PSS/E include: economic dispatch; reactive power scheduling; and location based marginal cost assessment. A wide set of objective functions include: minimise fuel costs; minimise active power slack generation; minimise active power loss; and minimise adjustable bus loads. The controlled parameters or constraints available to be considered include: bus voltage magnitude limits; branch flow limits; generator reactive power capability limits; and generator active power limits.

In this research, the OPF is used to determine an optimal solution for active and reactive power dispatch and OLTC tap change in a constrained voltage and line capacity environment. As all the scripted control mechanisms and case studies are modelled in Python (.py file), all necessary input data and control cases for the OPF formulation are also scripted into the Python file. The way PSS/E and Python are interfaced is that the .py file is executed (read) via PSS/E line by line. To implement the OPF application, the main elements for constraint and control data required in the .py file (from top to bottom) include:

- Open an OPF file: *psspy.ropf(r"""file_path""")*
- OPF constraints: bus voltage constraint data and branch flow constraint data;
- Generator dispatch data: generator bus, generator and cost table;
- Active power dispatch data: table number, maximum and minimum active power dispatch and fuel cost data for economic dispatch referenced by the generator dispatch data;
- Other constraints if needed;

- Objective function: minimise fuel cost for economic dispatch;
- Close OPF file: *psspy.nopf(0,1)*

### 6.3.2 Methodology

In the PSS/E OPF application, an economic dispatch analysis is employed with the objective to minimise the overall fuel costs and active power import from slack generation and to satisfy the voltage and line flow limits. In this way, the formulation is expected to provide an optimal dispatch of active and reactive power and tap adjustment such that the wind generation curtailment is minimised (i.e., to obtain the maximum wind generation export). The objective function (*f*) and constraint statements are provided in the following formulas:

$$\min f(C) = \sum_{g=1}^{n} c_g \times P_g \qquad (6 - 1)$$

subject to

$$P_{g,Min\ Avail} \le P_g \le P_{g,Max\ Avail} \qquad (6 - 2)$$

$$Q_{g,Min} \le Q_g \le Q_{g,Max} \qquad (6 - 3)$$

$$S_{Min} \le S \le S_{Max} \qquad (6 - 4)$$

$$V_{Min} \le V \le V_{Max} \qquad (6 - 5)$$

$$V_{Sub,Min} \le V_{Sub} \le V_{Sub,Max} \qquad (6 - 6)$$

where $C$ is the overall fuel costs, $c$ is the cost per unit output; $P$ and $Q$ are the active and reactive generation capacity of DG unit $g$ within the maximum and minimum capacity limit ($P_{g,Max\ Avail}$, $Q_{g,Max}$ and $P_{g,Min\ Avail}$, $Q_{g,Min}$); $S$ is the line loading capacity and $V$ is the DG bus voltage.

The economic dispatch searches for an optimal amount of active power output from the participating generators in order to serve demand and losses and to satisfy network limits at minimum fuel costs. Here, the power dispatch is adapted to a slightly different role. It is used to dispatch active power of wind DG unit so as to obtain a minimum amount of curtailed power, i.e., to encourage as much wind power exports as possible. This is obtained by assigning arbitrary 'fuel' costs to the wind or other DG units that participate in the optimisation. The strategy for setting the arbitrary cost is that a renewable (wind) DG unit will have zero cost so that the OPF encourages as much power export as possible during normal conditions and curtails wind output only when necessary (i.e., during constraints). The other unit, the slack generator will operate at a higher fuel cost to discourage imports [18]. In case more than one renewable generator with the same rated capacity participates, the unit with the largest capacity and located in the most susceptible area (more prone to voltage and line constraints) will have the second lowest cost so that it is given a priority to curtail power during constraints but is still encouraged to export power during normal situation. In this proposed strategy, for instance, the cost for a wind generator is set to \$1/MWh to encourage the power export while a nearby wind farm may use a more expensive cost (e.g., \$10/MWh). Such a priced-based strategy can be regarded as part of the 'Principles of Access' which explains the basis to manage power export of multiple DG units connected to distribution networks in order to overcome voltage and power flow constraints [98]. One example is called a 'Last In First Off' approach adopted in the ANM scheme in Orkney distribution network that where the last unit connected to the network be the first unit to curtail (or disconnect) [9, 12, 96]. Boehme *et al.* [18], used a similar pseudo-priced-based method but did not differentiate between locations.

Reactive power dispatch searches for the amount of reactive power required within the available active ($P_{g,Max\ Avail}$) and reactive power capability (i.e., a power factor range of 0.95 inductive/capacitive). The optimisation is performed by enabling the use of voltage control mode of the DG unit such that the bus voltage is maintained within a specified voltage target during the voltage constraint. The voltage target is the same as used previously in the decentralised scheme, i.e., 0.25% below the 6% maximum statutory limit (i.e., voltage upper limit is 1.06pu and voltage target is 1.0575pu). This allows the capability of the reactive power to be optimised. As shown in Figure 6 - 4 (previously presented in Chapter 4), the optimal reactive power is searched within the blue triangle ($\pm Q_{g,Max}$). However, this represents an overestimated reactive power range in which in real situation the DG power is curtailed ($P_{g,Curtailed}$) and the actual reactive power range is reduced to $\pm Q_{g,Max\ Curtailed}$

as seen in the shaded area. In tackling this issue, the author had attempted to investigate and use reactive power generation reserve and linear constraint equation functions within PSS/E. However, this proved not to be possible and the compromise outlined above was identified. Where the amount of (wind) active power dispatch used in the study is not large, the overrated reactive power capability is trivial and is assumed insignificant in the analysis. The yellow rectangle represents a fully-rated converter DG where the reactive power is available regardless the effect of generation curtailment.

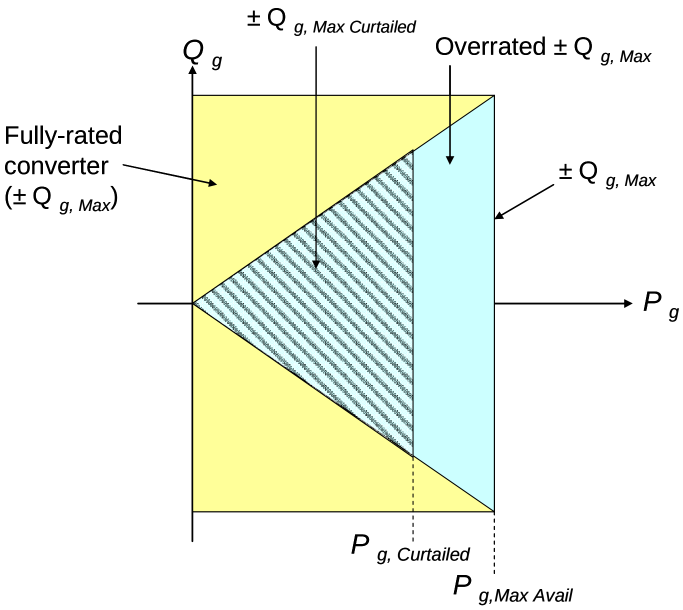



**Figure 6 - 4: DFIG active-reactive power capability for the OPF-based scheme**

Optimal tap adjustment is achieved in the OPF solution to regulate the controlled bus, in this case at the secondary bus of the transformer, to respect the maximum and minimum voltage target range and maintain the voltages in the rest of the network. In the analysis, the voltage range of ±3% of the nominal value (1.0pu) is used assuming that the range takes into account voltage variations of every bus in the network such that the maximum and minimum voltages are within the limits. This provides a substantial amount of additional flexibility in the optimisation.

In this research, a number of test cases have been undertaken to examine the performance of the PSS/E OPF in optimally coping with the voltage and thermal constraints. Different parameter settings of the centralised OPF-based scheme are investigated. The analyses are presented in the next subsection.

### 6.3.3 Investigation of centralised OPF for joint management

In the simulation study, the OPF is applied to optimise the system in real time, i.e., the OPF solution is performed at every time step so that the constraints are instantaneously monitored and mitigated. Here, the optimisation process generates an optimal solution for the dispatch of active and reactive power and the tap adjustment according to Equations 6 - 1 to 6 - 6. Hence, the dependent variables under consideration are active power ($P$), reactive power ($Q$) and tap adjustment to regulate substation (secondary) voltage ($V_{sub}$). To investigate the control behaviour of a centralised OPF voltage and thermal management and the effects of each variable on the control performance, four scenarios are studied: (1) effect of $P$ dispatch; (2) effect of $Q$ dispatch; (3) effect of $P$ and $Q$ dispatch and (4) effect of substation tap adjustment with 3 sub-scenarios – optimising $V_{sub}$ only; optimising $P$ dispatch and $V_{sub}$; and optimising $P – Q$ dispatch and $V_{sub}$.

All scenario studies are carried out in the 12-bus 33kV distribution network (as used previously in Chapter 4). The one-minute load and wind generation profiles over one day in England as depicted in Figure 6 - 5 (top) are applied. To clearly illustrate the responses, the one-day simulation period is zoomed-in on an hour between 00:00 to 01:00 as shown in Figure 6 - 5 (bottom). The wind farms at buses 11 and 12 operate at 6-MW rated capacity. The fuel cost settings for the economic dispatch analysis, Cases A to C, as shown in Table 6 - 2 are applied. In Case A, the costs of the wind units at buses 11 and 12 are assigned equally at \$1/MWh as a base case so that both units are encouraged to generate power as much as possible while a slack generator fuel cost is more expensive to minimise imports. The actual currency is entirely arbitrary. Case A provides optimal operation (i.e., active and reactive power output) of the two wind farms based on the wind farm that will likely be the most effective to manage constraints at that instant. In Case B, the cost of wind unit at bus 11 is 10 times more expensive than that at bus 12 assuming that the wind unit at bus 12 is preferred to export more power output. This also dictates that during voltage rise and/or line overload wind farm bus 11 will likely be constrained first to minimise the overall 'fuel' costs. The cost Case C, on the other hand, assumes that the wind unit at bus 11 is preferred to export more power output therefore is assigned the cheapest. In action, similarly, active power curtailment will likely be applied at wind farm bus 12 during constraints. The cost cases B and C will be used later in the performance assessment (Section 6.4).

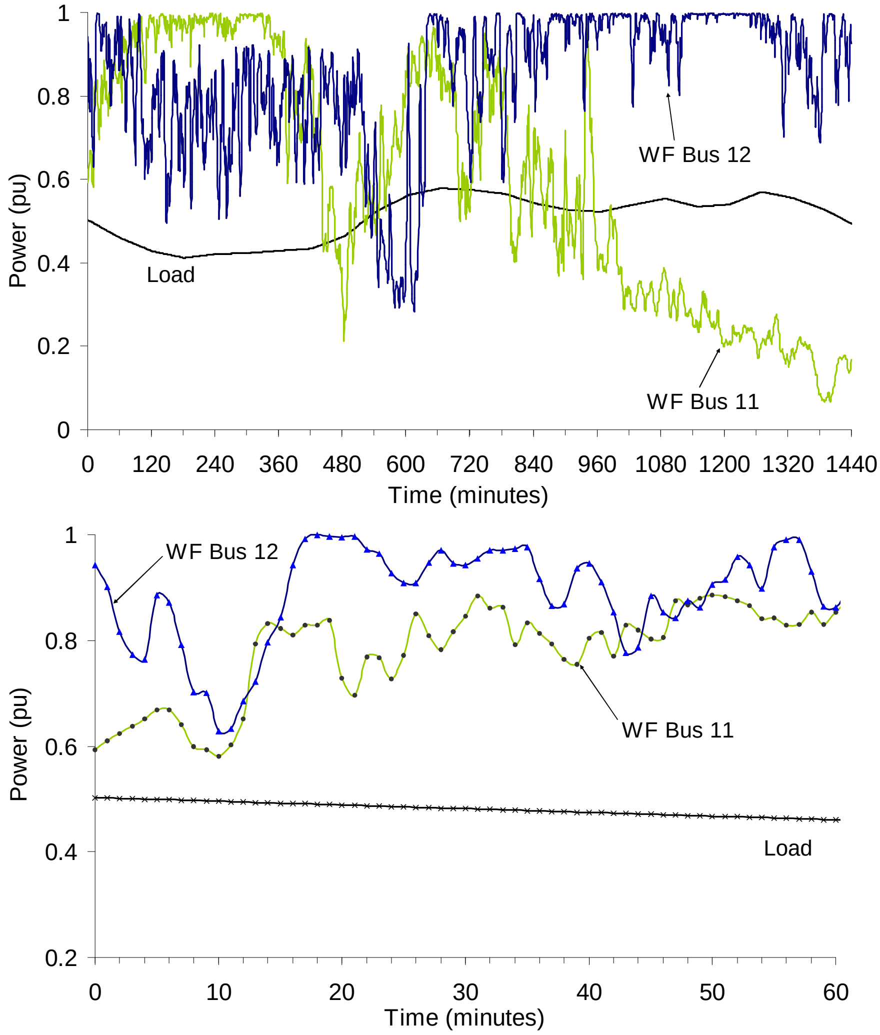



**Figure 6 - 5: (Top) one minute time-step load and wind generation profiles on 1st February 2010 and (bottom) zoomed-in plots between 00:00 to 01:00**

**Table 6 - 2: 'Fuel' cost table of DG for the OPF economic dispatch. Note: $/MWh is an Arbitrary Currency Unit used in PSS/E OPF**

| Types | Case A<br>Fuel cost ($/MWh) | Case B<br>Fuel cost ($/MWh) | Case C<br>Fuel cost ($/MWh) |
|---|---|---|---|
| Slack generator | 100 | 100 | 100 |
| Wind bus 11 | 1 | 10 | 1 |
| Wind bus 12 | 1 | 1 | 10 |

The definition of each scenario is:

- **Scenario 1: Effect of *P* dispatch (fixed *Q*, varied *P*).** This scenario shows the effect of active power curtailment in managing the constraints. The *Q* capability is fixed at unity power factor and the substation voltage is fixed. The fuel costs for economic dispatch in Cases A and B are used.

- **Scenario 2: Effect of *Q* capability (unconstrained *P*, varied *Q*).** This scenario shows the effect of reactive power adjustment in managing the constraints when the DG unit is equipped with a fully rated converter. The *Q* capability ranges are 0.95 and 0.9 power factor and the substation voltage is fixed. The fuel cost in Case A is used.

- **Scenario 3: Effect of *P* and *Q* dispatch (varied *P* and *Q*).** This scenario shows the effect of the combined active and reactive power adjustment in managing the constraints when the DG unit is equipped with a fully rated converter and a generation curtailment scheme. The *Q* capability range is 0.95 power factor and the substation voltage is fixed. The fuel costs in Cases A and B are used.

- **Scenario 4: Effect of optimal tap adjustment ($V_{sub}$).** This scenario shows the effect of tap adjustment together with the combined active and reactive power in managing the constraints. The following three sub-scenarios are carried out:

a. Zero $Q$ capability (unity power factor), fuel cost Case A, $V_{sub}$ allowed to vary within ±3%.

b. $Q$ fixed at 0.95 inductive, fuel cost Case B, $V_{sub}$ allowed to vary within ±3%.

c. $Q$ capability range at 0.95 inductive/capacitive, fuel cost Case B, $V_{sub}$ allowed to vary within ±3%. This is a full OPF approach where all parameters are fully visible and optimised.

In Scenarios 1 to 3, the OLTC tap ratio is fixed (at middle position). This will tend to exaggerate the voltage rise problem and will not be a precise representation of real transformer operation. This would be developed in the same way as Boehme *et al.* [18] and [124, 125] by constraining the substation voltage to 1pu which approximates non-optimal tap operation.

In scenario 1, only active power dispatch optimisation is performed with the wind farms at buses 11 and 12 operating at unity power factor and the tap adjustment fixed. As shown in Figure 6 - 6, a great reduction of the line flows between buses 10-12 (top right) can be observed due to the wind output of both sites are being curtailed (bottom); (the voltages at both locations are also maintained below the voltage limit as a consequence). In minimising the overall costs and slack generation, such a restricted approach is essentially due to an attempt to comply with the voltage and line capacity limits as well as to maintain the network losses and load.

In scenario 2 (Figure 6 - 7), the effect of reactive power dispatch alone reveals fairly different results from scenario 1. The voltage profiles (top left) slightly fluctuate during the beginning until around minute 14 when the voltages exceed the upper limit and the OPF then maintains the voltages around the target value by adjusting reactive power. The OPF with $Q$ dispatch optimally assigns the wind farm bus 12 to absorb reactive power (bottom left) whilst the wind farm bus 11 to be more capacitive (bottom right). The amount of reactive power dispatch also depends on the power factor capability. More reactive power production or absorption is seen at higher power factor capability (0.9 power factor). The line loading between buses

10-12 (top right) at all power factor settings are decreased below the maximum flow. However, overload is observed between minutes 16 to 24 for the 0.9 power factor case due to larger reactive power flows caused by the overrated reactive power capability. Of the 0.95 and 0.9 power factor approaches, the line loadings are slightly higher due to the reactive power flow exchange.

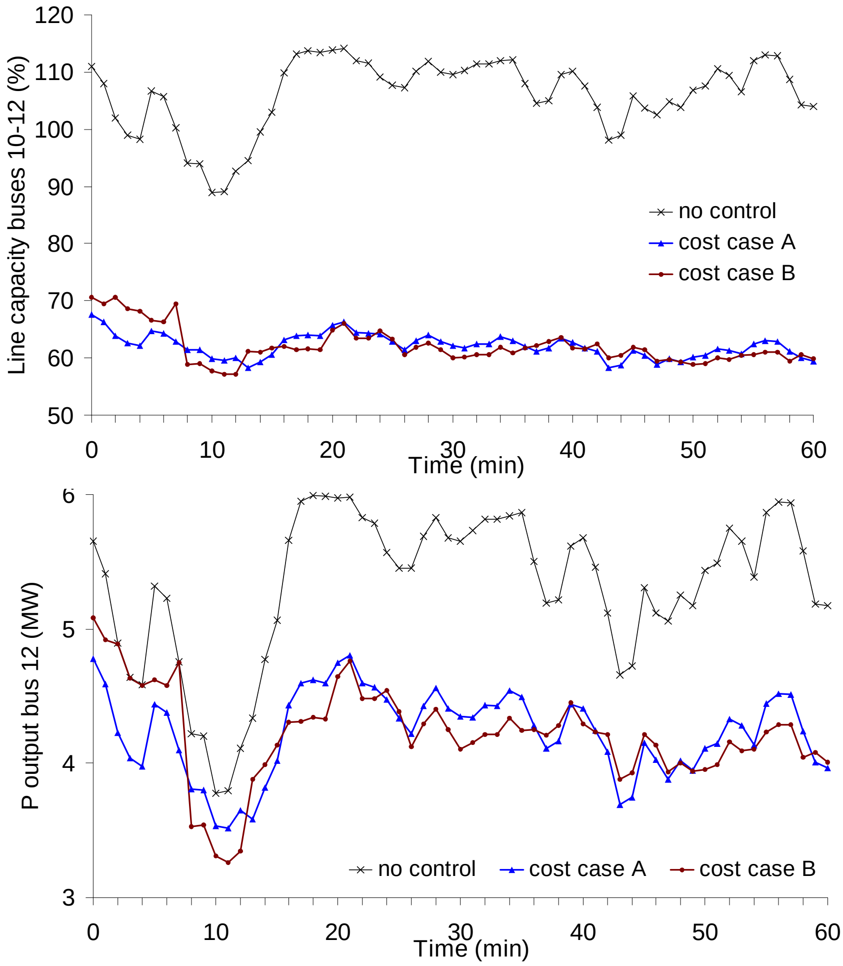



**Figure 6 - 6: Line capacity buses 10-12 and power output of DG bus 12 for Scenario 1 ($V_{sub}$ and Q capability are fixed)**

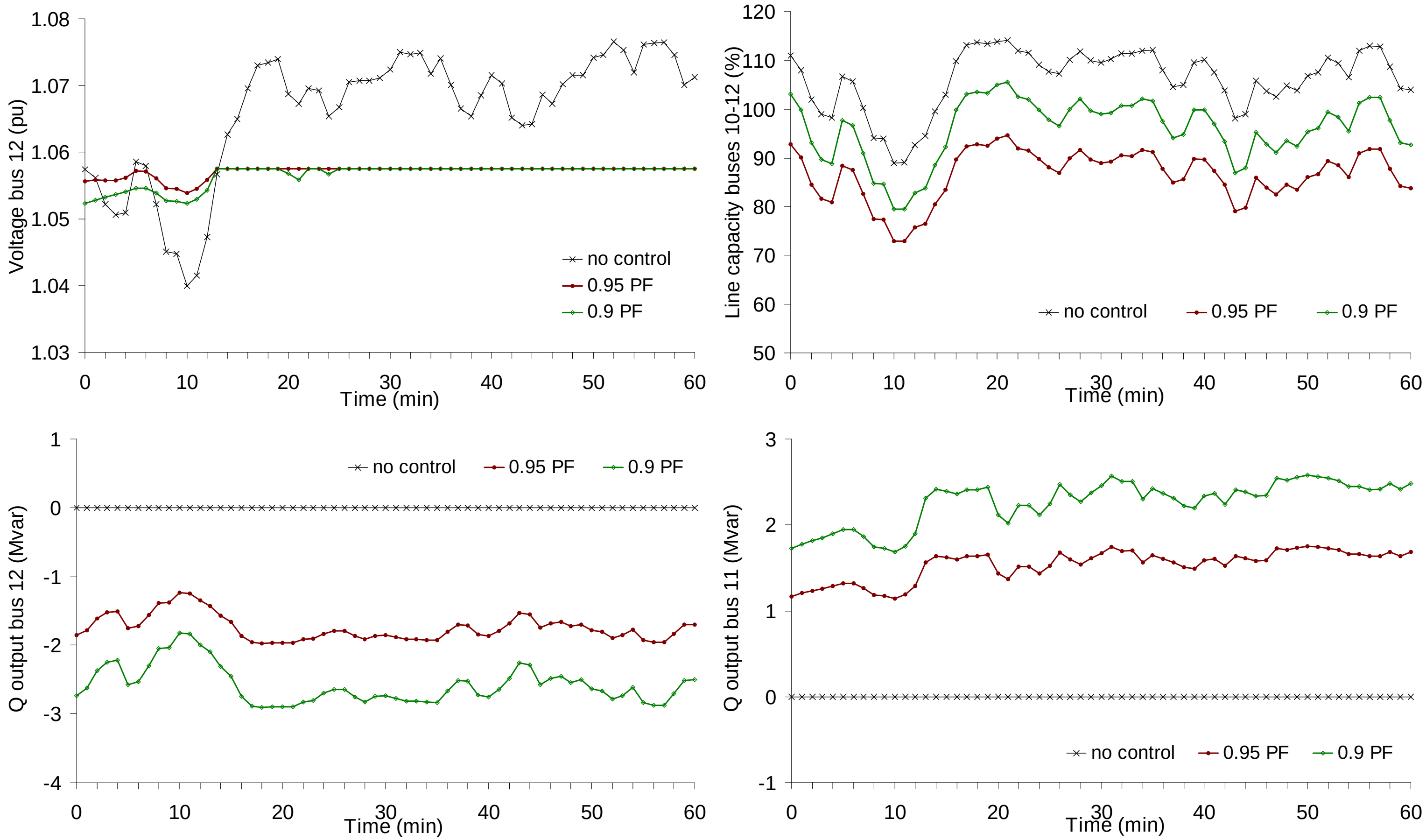



**Figure 6 - 7: Voltage profiles bus 12, line capacity buses 10-12 and reactive power output of DG buses 11 and 12 for Scenario 2 (Cost A and fixed $V_{sub}$)**

In scenario 3 (Figure 6 - 8), active and reactive power dispatch are used. The voltage profiles at bus 12 (top left) are again maintained below the maximum voltage limit in irrespective spite of the ‘fuel’ cost setting. This effect is also seen on the voltage bus 11. During the first 12 minutes, the voltages are maximised around the target value as a result of the wind farm bus 11 being capacitive (similar to that in scenario 2) which also affects the voltage at bus 12 (provided that the locations are electrically close). The changes in active power are also observed. The wind farm at bus 12 is required to curtail its power export (bottom right) while operating at more inductive power factor (bottom left). With the impact of restricting the active power export, the line loadings are reduced to around 80% and 90% consequently (top right).

In scenario 4, the effect of tap adjustment is studied. In sub-scenario a (Figure 6 - 9) where the wind farms operate at unity power factor with fuel costs set equally, the voltage profiles at bus 12 (top left) are maintained below the maximum voltage limit as a result of the tap action (bottom right). By allowing the capability of the OLTC to be optimised, variations in active power output are eliminated. During the periods where the loading exceeds the flow limit, the line loading headroom is maximised (top right), i.e., close to the target flow of 95.5% of maximum capacity as a result of the wind farm’s active power being restricted (constant around 4.4-MW). At bus 11, the wind farm is observed to generate at its rated capacity without the need for curtailment. Optimal tap adjustment at higher positions (i.e., lower substation voltage by tapping up) is also observed (bottom right) to maintain the voltage target (as the voltage rise occurred from minute 16 and over the whole period). The OLTC transformers change tap 17 times during the test period, with the highest tap position of 24.

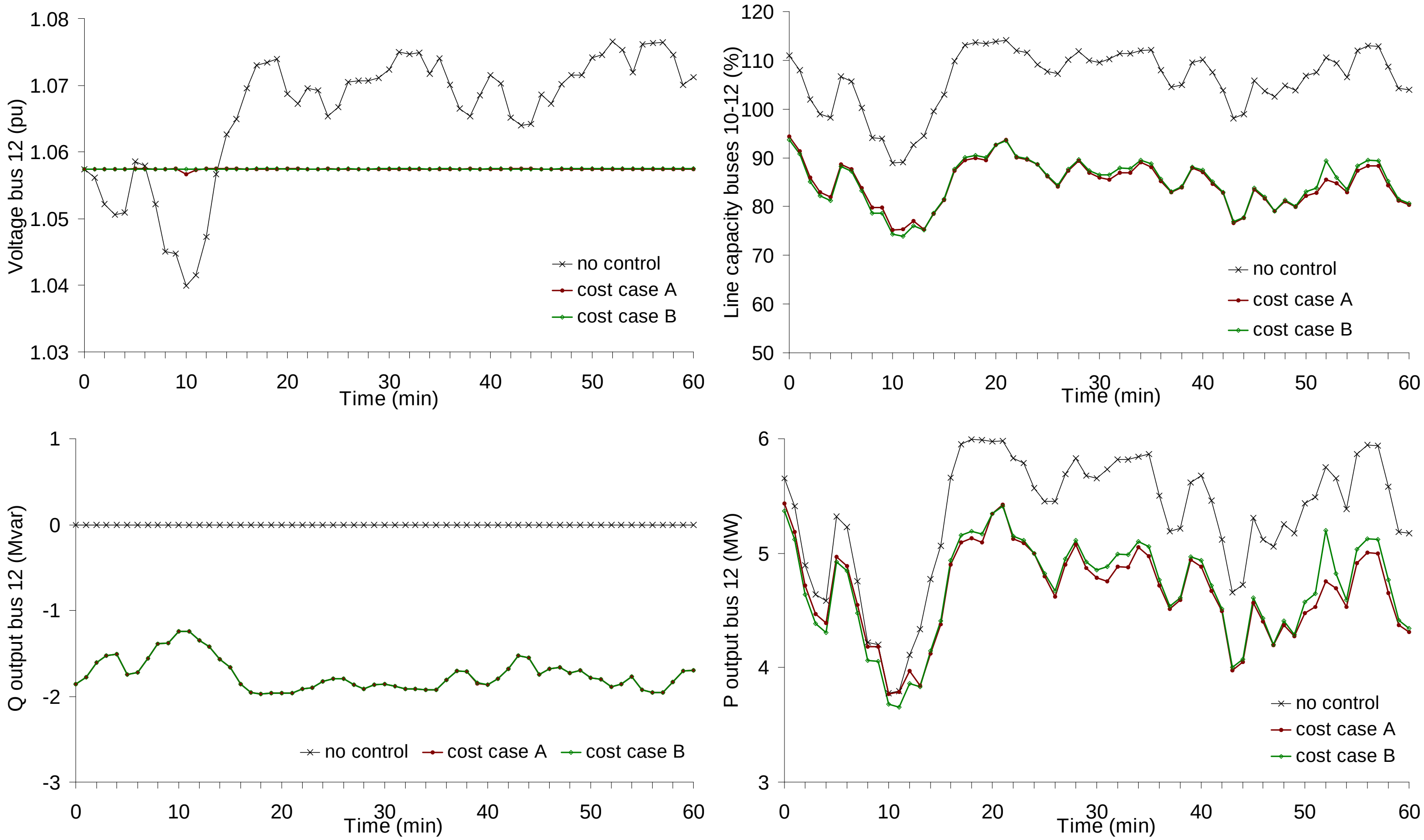



**Figure 6 - 8: Voltage profiles bus 12, line capacity buses 10-12 and reactive and active power output of DG bus 12 for Scenario 3 (PF range of 0.95 inductive/capacitive, fixed $V_{sub}$)**

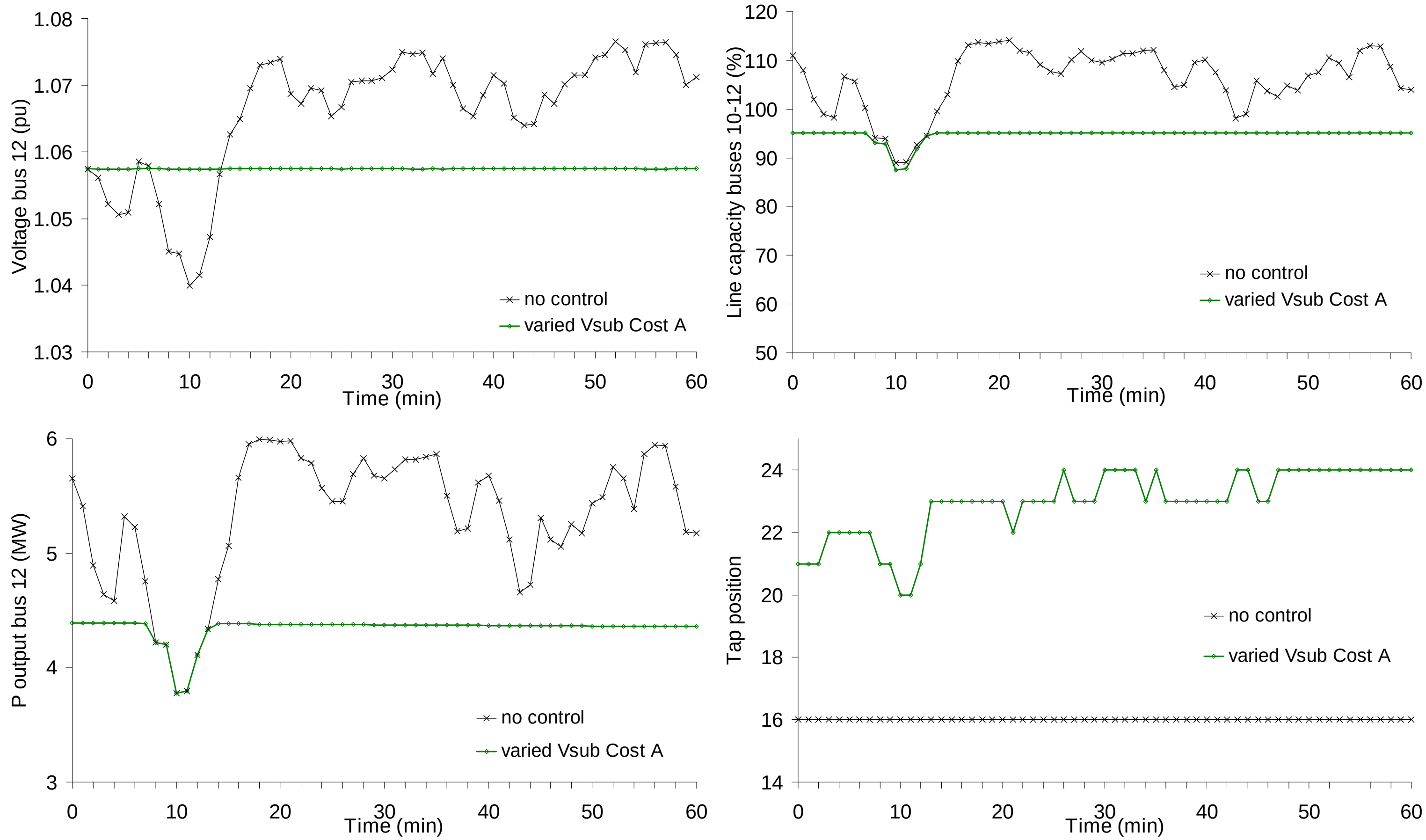



**Figure 6 - 9: Voltage profiles bus 12, line capacity buses 10-12 and active power output of DG bus 12 and tap position (middle tap = 16th) for Scenario 4a (unity PF, Cost A, ±3% $V_{sub}$)**

In sub-scenario b (Figure 6 - 10), both wind farms are required to operate at 0.95 inductive power factor and the cheapest fuel cost assigned for wind farm at bus 12. Consequently, the voltage at bus 12 (top left) is maintained below the voltage upper limit. With the substation voltage target being flexible, the voltage is greatly reduced as a result of the tap change (bottom right) that enlarges the effect of inductive power factor of the wind farm. This means that greater voltage headroom can be obtained. Similar voltage profiles are also seen at bus 11. The flexible tap adjustment case also results in the power export of wind farm bus 12 being constrained to around 4-MW (bottom left), which is lower than that in the previous case, in order for the line loading to be maintained below the maximum line limit (top right) due to the added reactive power flows.

In sub-scenario c (Figure 6 - 11), the dispatch of active and reactive power and the tap adjustment depicting a fully optimised scheme are applied in the OPF process. The voltages (top left) are maintained around the voltage target as a result of the tap and reactive power adjustments. The wind export is restricted to around 4.4-MW (middle right) as a result of an attempt to maximise the line flow around the maximum line flow target (top right). This is similar to the previous case (sub-scenario b). The tap is adjusted 7 times with the highest tap at position 28 (bottom). The changes in tap cause the wind farm to mostly become capacitive during the period (middle left). This is likely to be caused by the tap being at high position and that the reactive power export is required to raise the voltage.

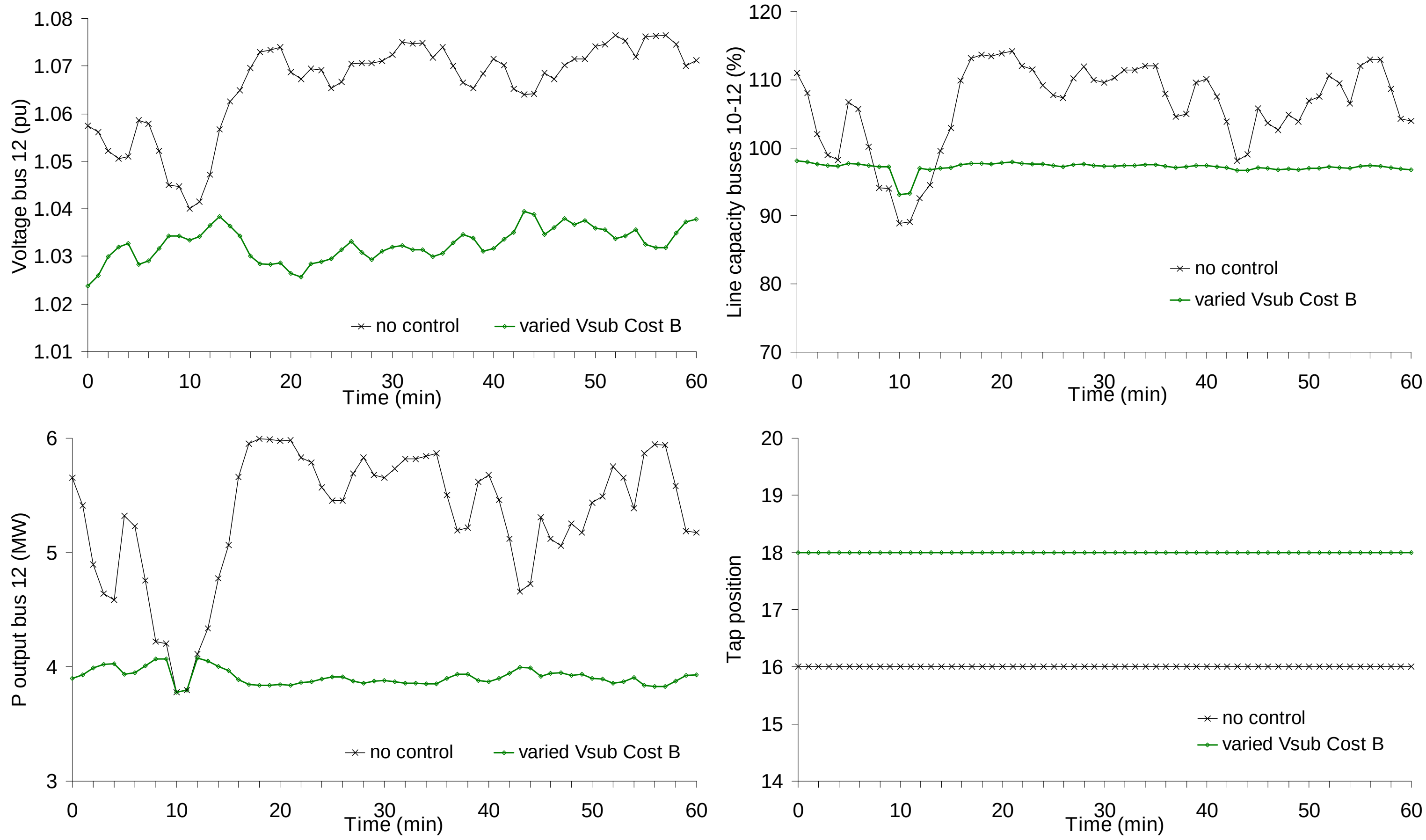



**Figure 6 - 10: Voltage profiles bus 12, line capacity buses 10-12, active power output of DG bus 12 and tap position (middle tap = 16th) for Scenario 4b (PF fixed at 0.95, Cost B, ±3% $V_{sub}$)**

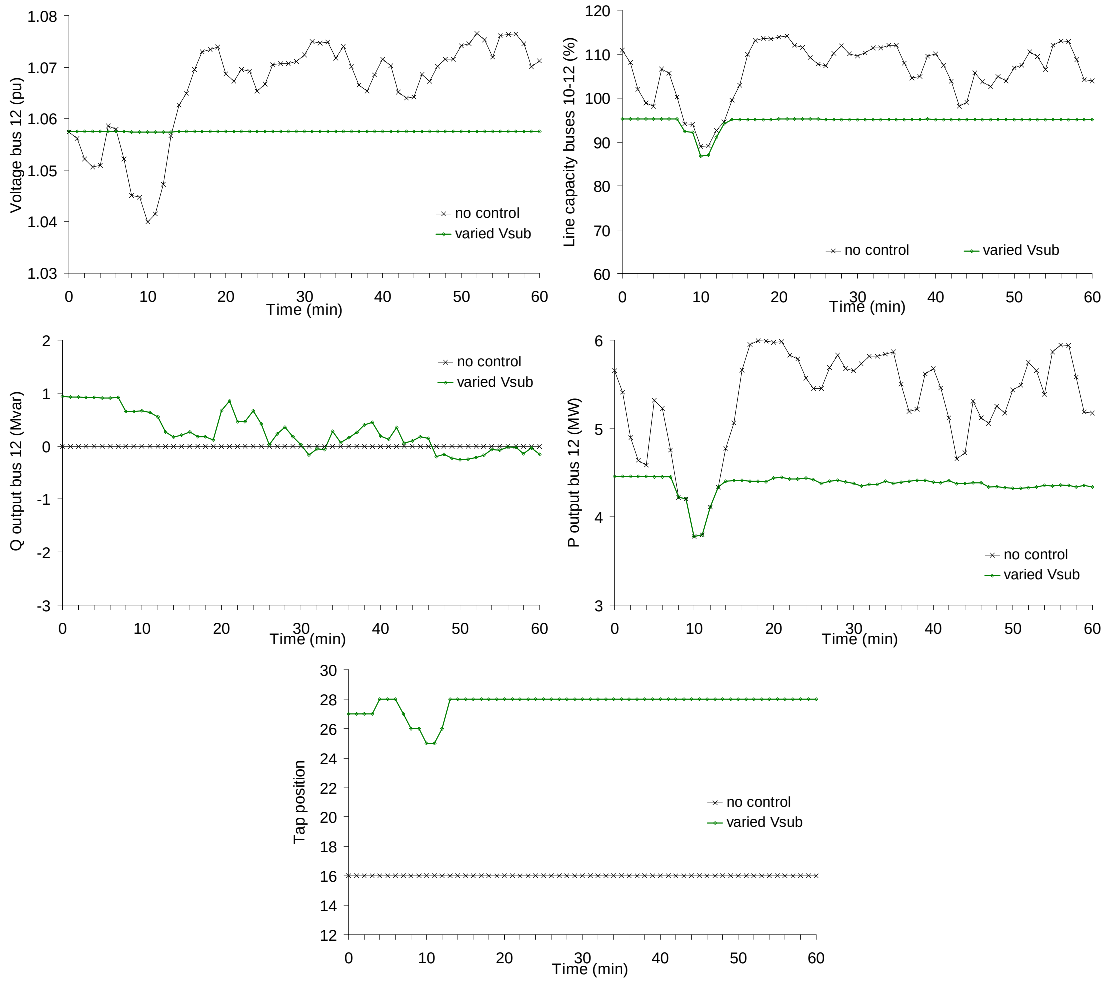



**Figure 6 - 11: Voltage profiles bus 12, line capacity buses 10-12, reactive and active power output of DG bus 12 and tap position (middle tap = 16$^{th}$) for Scenario 4c (PF range at 0.95 inductive/capacitive, Cost B, ±3% $V_{sub}$)**

In all sub-scenarios (4a, 4b and 4c), it is revealed that an optimal tap adjustment approach can enable the active and reactive power dispatch with voltage and line capacity constraints to be more effectively optimised compared to the fixed tap approach. As investigated, the optimal solutions obtained from employing the PSS/E OPF tool are able to satisfy the voltage and line capacity limits. From the author's viewpoint however the optimal adjustment of all variables (i.e., active power, reactive power and tap position) may not always necessarily provide the best solution in terms of maximising the wind exports without excessively compromising or restricting the wind farm operation. With this in mind, the control performance of the decentralised schemes (presented in Chapters 4 and 5) and the centralised management as presented earlier will be assessed and compared in the case studies.

## 6.4 Case Study: Coordinated and OPF-based Joint Voltage and Thermal Management

This section examines the effectiveness of the two schemes presented previously. The case studies are carried out using more complex rural distribution networks in order to characterise the constraint situations and test the control performance potentially close to practical operation. A combined case study for the voltage and thermal management coordinated OLTC (V&T Mgt OW TAP) and the OPF-based joint management with fully integrated optimisation (OPF-based V&T Mgt) is analysed and compared.

The study is carried out on a minute time step over one day using the 12-bus 33kV distribution network (previously used in Chapter 4, reproduced as Figure 6 - 12). The demand and two wind farms profiles over one day (1440 minutes) in Figure 6 - 5 (top) are applied. In order to imitate real operation, the V&T Mgt coordinated OLTC scheme operating with persistence forecasting while the 'perfect' OPF-based V&T Mgt is assumed to perfectly forecast demand and wind.

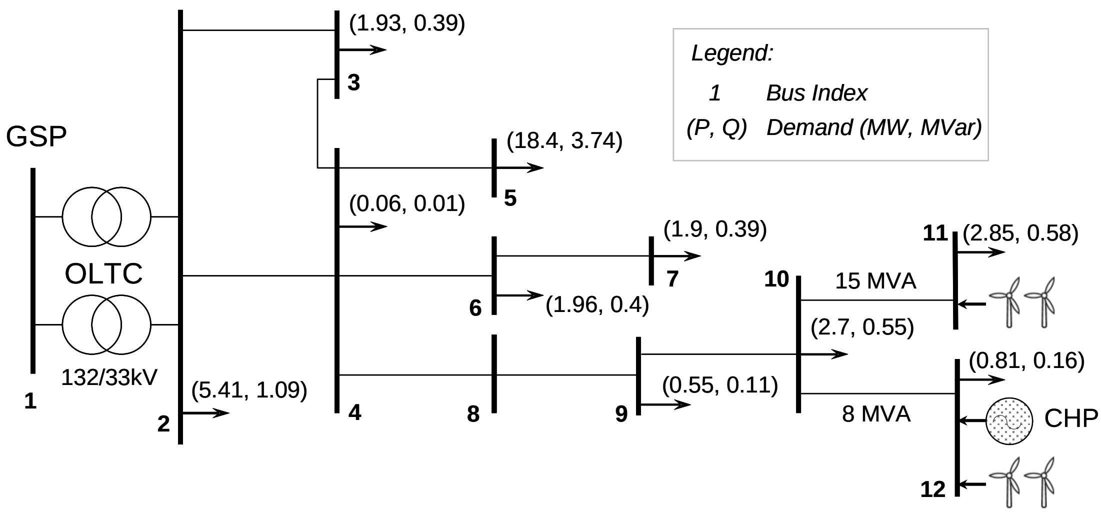



**Figure 6 - 12: Modified 12-bus 33kV rural distribution network (UK GDS [120])**

Plots for voltage profiles, reactive power, tap actions, line loading and active power output are presented in Figure 6 - 13 to Figure 6 - 15. Without control, the voltage problem at bus 11 occurs during the first 7 hours of simulation. This incidence is similar to bus 12 due to high wind resources at both sites. Overall, all schemes show effective voltage mitigation in maintaining the voltages below the upper limit (Figure 6 - 13 (top) and Figure 6 - 14 (top)). The inductive/capacitive reactive power limit varies as it is affected by variable wind resources. The variations in voltages are seen for the voltage management coordinated OLTC (V Mgt OW TAP, presented for comparison only) and V&T Mgt OW TAP while the OPF-based scheme shows its high capability in dealing with such variability. This is the effect of combined actions from active and reactive power dispatch and tap adjustment provided by the optimisation. Considering the reactive power adjustment however the OPF-based scheme requires the wind farms to adjust the power factor frequently over the whole period while the schemes without optimisation request power factor adjustment only when necessary (Figure 6 - 13 (bottom) and Figure 6 - 14 (middle)). Provided that the optimisation is able to improve voltage variations, nonetheless, the wind farm bus 11 is required to continually operate at its full power factor capability (i.e., at 0.95 capacitive) while at bus 12 the wind farm absorbs reactive power during voltage rise and switch to produce reactive power for the remaining period. For the tap adjustment as shown in Figure 6 - 14 (bottom), it is observed that the change in tap is extreme for the case with optimisation that attempts to maintain the voltages smoothly.

The advantage of employing the optimisation tool is also witnessed on the line flows between buses 10-12 (Figure 6 - 15). The OPF-based scheme shows more effective function in keeping the loading within the line limit compared to the joint management without optimisation. This is a result of the optimal active power dispatch that strictly constrains the power output (to around 4.4-MW). For the joint voltage and thermal management coordinated OLTC the overload problem cannot completely be managed as seen around the first 8 hours of simulation. This occurs over short periods as a consequence of the operational gap between requesting tap action and assigning curtailment set points to the wind farm during voltage rise.

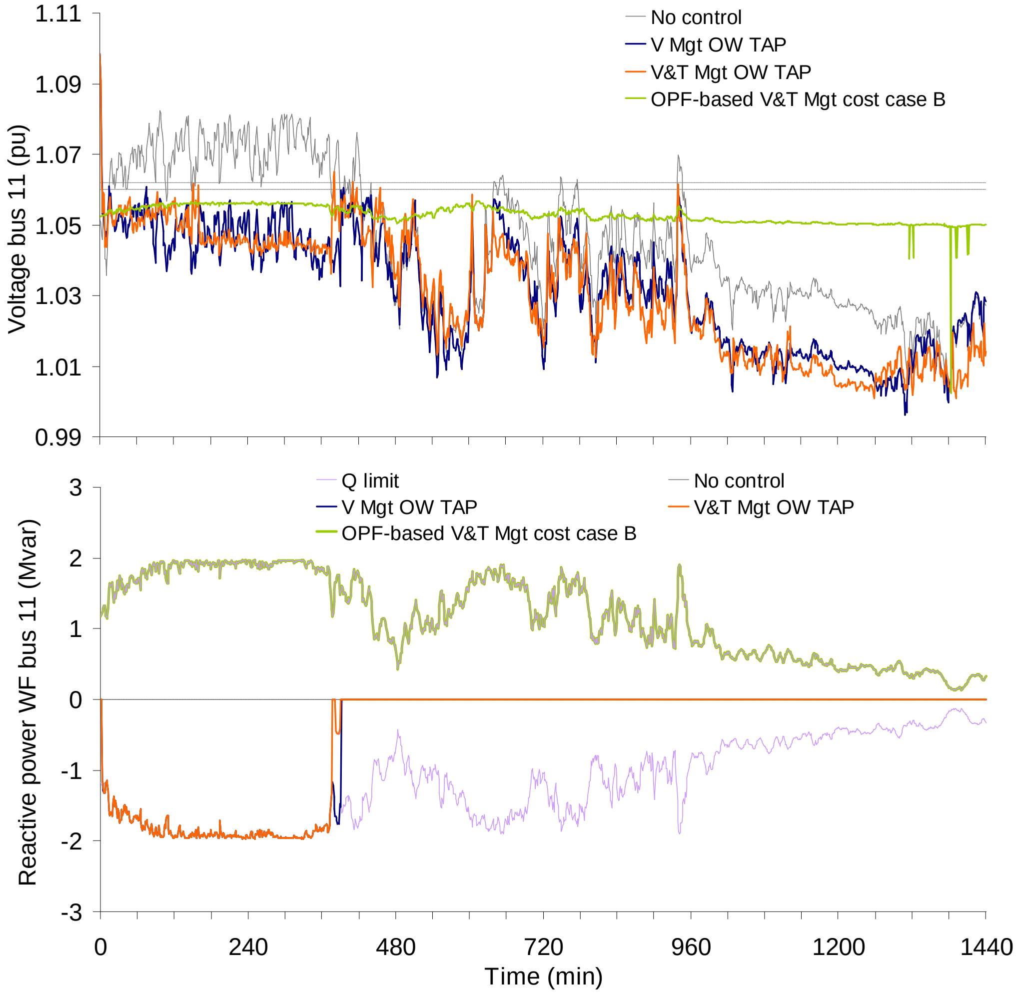



**Figure 6 - 13: (Top) voltage profiles and (bottom) reactive power at bus 11 for performance comparisons of the voltage management coordinated OLTC, the joint management coordinated OLTC and the OPF-based schemes**

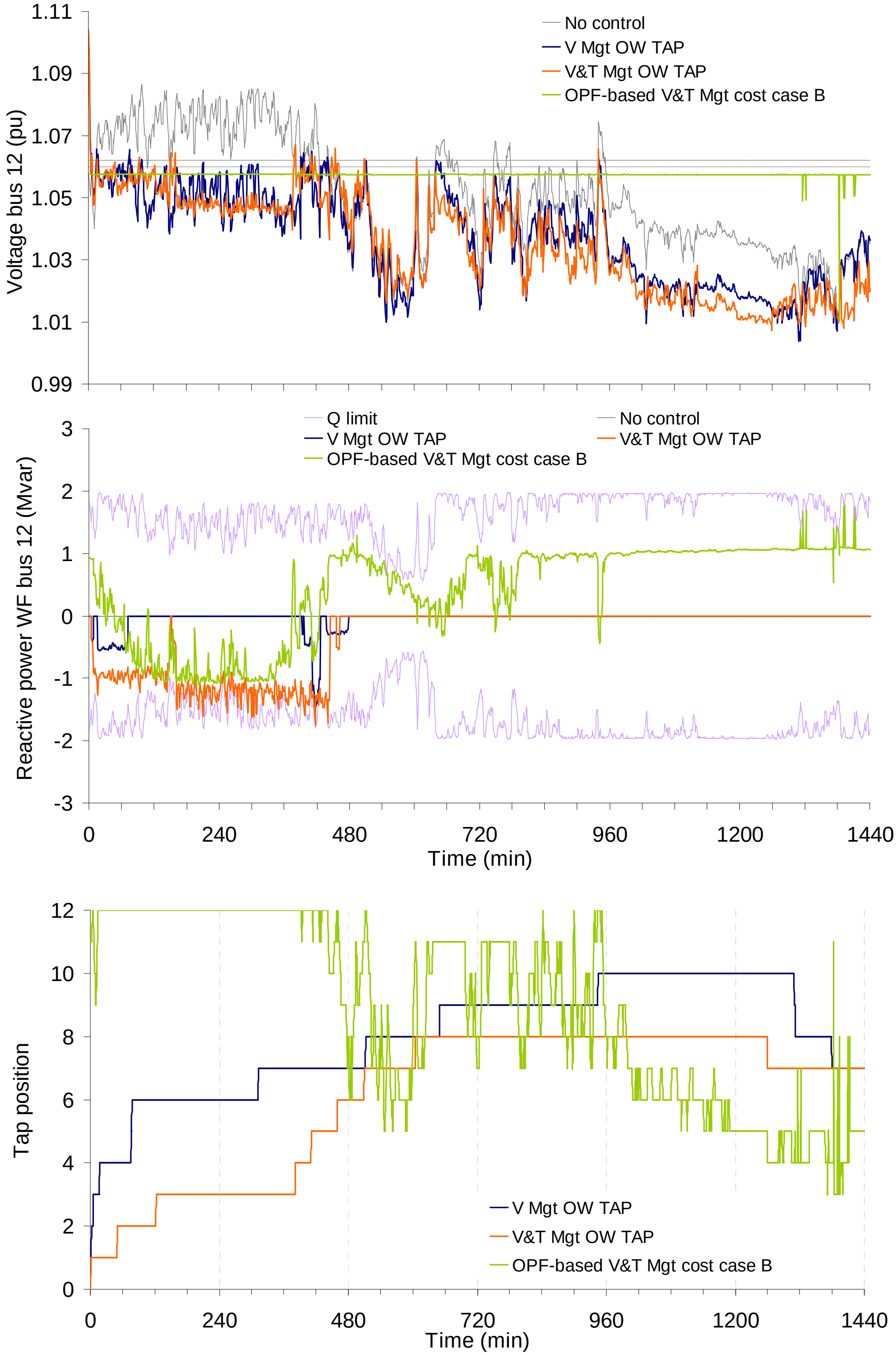



**Figure 6 - 14: (Top) voltage profiles, (middle) reactive power at bus 12 and (bottom) OLTC Tap actions for performance comparisons of the voltage management coordinated OLTC, the joint management coordinated OLTC and the OPF-based schemes**

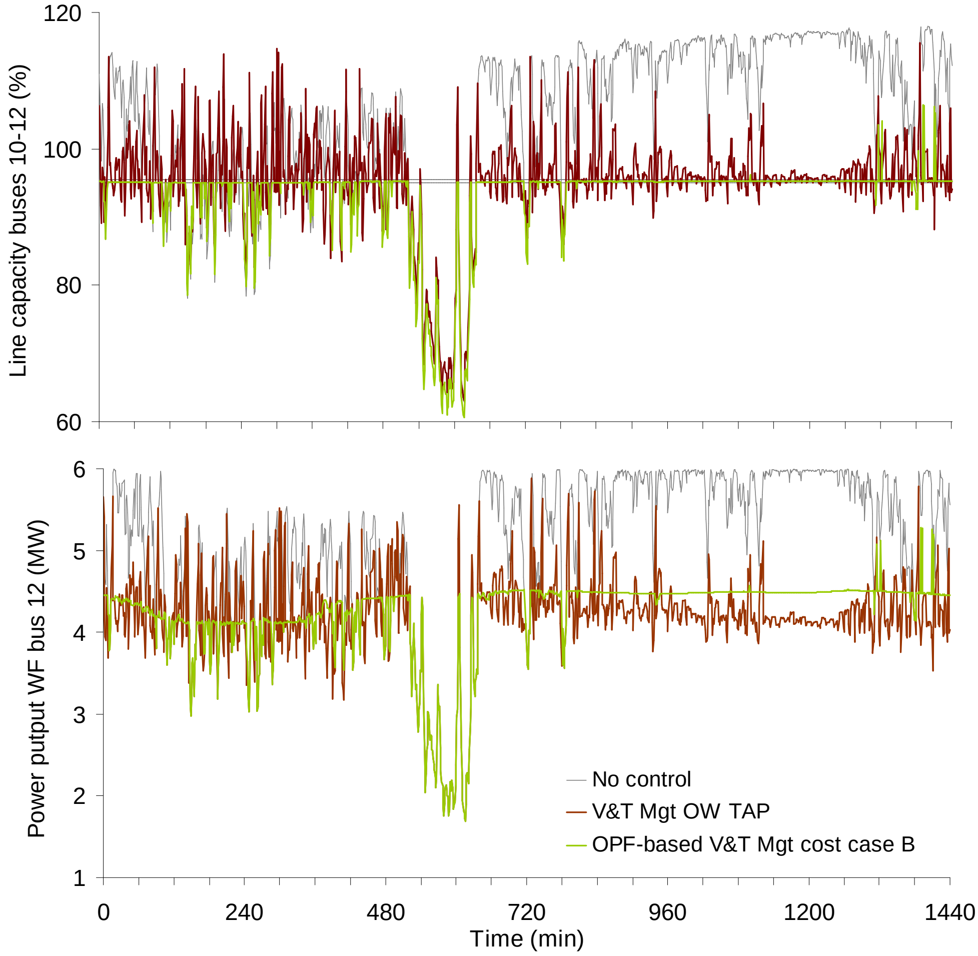



**Figure 6 - 15: (Top) line loading buses 10-12 and (bottom) power output bus 12 for performance comparisons of the joint voltage and thermal management coordinated OLTC and the OPF-based schemes**

Performance comparison obtained from the case studies is also summarised in Table 6 - 3. The results confirm that despite requiring frequent adjustment of the reactive power (greater amount of reactive power exchanges) and the tapping action, the OPF-based scheme proves its advantage in voltage rise and overload mitigation with a slightly higher capacity factor (less energy lost in curtailment) of the wind farm at bus 12.

**Table 6 - 3: Performance comparison of the voltage and thermal management with coordinated OLTC and with OPF tool (one day simulation period)**

| Schemes → Measures ↓ | No control $2 \times$ 3-MW | Coordinated V Mgt OW TAP $2 \times$ 6-MW | Coordinated V&T Mgt OW TAP $2 \times$ 6-MW | OPF-based V&T Mgt cost Case B $2 \times$ 6-MW |
|---|---|---|---|---|
| Overvoltage Bus 11 (1.06pu) | None | 0.49% | 0.83% | None |
| Overvoltage Bus 12 (1.06pu) | None | 4.44% | 2.78% | None |
| Overload Line 10-12 (100%) | None | 73.13% | 15.07% | 0.42% |
| Energy export Bus 11 (MWh/day) | 42.9 | 85.9 | 85.9 | 85.9 |
| Energy export Bus 12 (GWh/day) | 60.9 | 121.7 | 99.7 | 101.5 |
| Capacity factor Bus 11 | 0.6 | 0.6 | 0.6 | 0.6 |
| Capacity factor Bus 12 | 0.84 | 0.84 | 0.69 | 0.7 |
| Overall curtailed energy losses | None | None | 22 MWh/day Bus 12 | 20.3 MWh/day Bus 12 |
| Reactive power Bus 11 (cumulative Mvarh) | None | 11.86 inductive | 11.5 inductive | 28.2 capacitive |
| Reactive power Bus 12 (cumulative Mvarh) | None | 1.1 inductive | 8.3 inductive | 15 capacitive 4.5 inductive |

## 6.5 Overall Performance Comparisons

The control actions of the coordinated joint voltage and thermal management and the OPF based scheme have been presented. In order to assess their overall performance, these schemes are compared directly against several of the decentralised schemes detailed in Chapters 4 and 5 with the same network and wind/demand conditions. The schemes considered are:

- decentralised joint voltage and thermal management (V&T Mgt);
- operational windows decentralised voltage and thermal management (V&T Mgt OW);
- joint voltage and thermal management with operational windows coordinated OLTC (V&T Mgt OW TAP);
- OPF-based centralised scheme with cost Cases B and C (OPF-based V&T Mgt).

The network used is the modified 12-bus 33kV distribution network with one CHP unit at bus 12 and two wind farms each sited at buses 11 and 12. The assessment is carried out over one year in 2003 and is for the same conditions used in Chapter 4. For the OPF-based scheme, two cost Cases (B and C) for the active power dispatch as shown in Table 6 - 2 are examined and compared. The equal share case (case A) is not considered here in order to emphasise the implications of alternative network access principles. Again in order to mimic real operation, all schemes except the OPF cases assume persistence forecasting.

Table 6 - 4 summarises the overall performance of the four different novel schemes on the basis of voltage and line flow management, net energy export, wind capacity factor, system energy losses and reactive energy production/consumption of each wind farm. Each of the performance comparisons is discussed in detail in the following subsections.

**Table 6 - 4: Overall performance comparisons**

| Schemes → Measures ↓ | No control 2 × 3-MW | V&T Mgt 2 × 6-MW | V&T Mgt OW 2 × 6-MW | Coordinated V&T Mgt OW TAP 2 × 6-MW | OPF-based V&T Mgt cost Case B 2 × 6-MW | OPF-based V&T Mgt cost Case C 2 × 6-MW |
|---|---|---|---|---|---|---|
| Overvoltage Bus 11 (1.06pu) | None | None | 1.15% | 0.1% | None | None |
| Overvoltage Bus 12 (1.06pu) | 0.21% | 2.4% | 7.74% | 1.06% | None | None |
| Overload Line 10-11 (100%) | None | None | None | None | None | None |
| Overload Line 10-12 (100%) | None | 0.1% | 0.1% | 0.12% | None | 0.07% |
| Energy export Bus 11 | 10.8 GWh/year | 21.71 GWh/year | 21.7 GWh/year | 21.71 GWh/year | 21 GWh/year | 21.71 GWh/year |
| Energy export Bus 12 | 12.6 GWh/year | 21.69 GWh/year | 21.53 GWh/year | 21.83 GWh/year | 22.4 GWh/year | 18.8 GWh/year |

**Overall performance comparisons (continued)**

| Schemes → Measures ↓ | No control $2 \times$ 3-MW | V&T Mgt $2 \times$ 6-MW | V&T Mgt OW $2 \times$ 6-MW | Coordinated V&T Mgt OW TAP $2 \times$ 6-MW | OPF-based V&T Mgt cost Case B $2 \times$ 6-MW | OPF-based V&T Mgt cost Case C $2 \times$ 6-MW |
|---|---|---|---|---|---|---|
| Capacity factor Bus 11 | 0.41 | 0.41 | 0.41 | 0.41 | 0.4 | 0.41 |
| Capacity factor Bus 12 | 0.48 | 0.41 | 0.41 | 0.415 | 0.42 | 0.36 |
| System energy losses | 4.45 GWh/year | 6.1 GWh/year | 6.2 GWh/year | 5.9 GWh/year | 5.6 GWh/year | 5.9 GWh/year |
| Energy lost in curtailment Bus 11 | N/A | None | 0.01 GWh/year | None | 0.71 GWh/year | None |
| Energy lost in curtailment Bus 12 | N/A | 3.54 GWh/year | 3.7 GWh/year | 3.4 GWh/year | 2.83 GWh/year | 6.43 GWh/year |
| Reactive power Bus 11 (cumulative Mvarh) | None | 11.3 capacitive 683 inductive | 0.156 capacitive 2,531 inductive | 99.91 inductive | None | None |
| Reactive power Bus 12 (cumulative Mvarh) | None | 7.9 capacitive 1,635 inductive | 0.085 capacitive 3,699 inductive | 1,991 inductive | 8,295 capacitive | 8,295 capacitive |

### 6.5.1 Effectiveness in Voltage and Line Flow Management

Of all schemes, the OPF-based voltage and thermal management using cost Case B (which favours production at DG bus 12) shows the most effective performance in that over the simulation period it is able to completely mitigate the voltage rise and line overload constraints. Using cost Case C (DG bus 11 is the cheapest) in the OPF-based scheme, minor overload problem in line 10-12 occurs (i.e., 0.07%). This could be due to a sudden wind peak that would last for very short period and that the line was able to cope with. The operational windows decentralised voltage and thermal management are the least effective in managing the constraints as there are times of voltage rise and line overload occurrence, i.e., 1.15% overvoltage at bus 11, 7.74% overvoltage bus 12 and 0.1% overload line 10-12. This is a result of the holding time mechanism of the operational windows which assumes the DNOs allow a rather flexible framework to ensure the control actions are certainly required in order to maximise power exports (i.e., reducing the need for curtailment). Employing the same control algorithm but with the coordinated OLTC operation, the control performance on voltage and line capacity management is improved. The voltage problems at both sites are greatly reduced (to 0.1% and 1.06% on buses 11 and 12, respectively) however it marginally increases the duration of overloads on line 10-12. The original decentralised voltage and thermal management shows moderately good performance leaving only trivial periods of overvoltage at bus 12 and line 10-12 overload. It is notable that in this case the full OPF system does not deliver substantially better performance.

### 6.5.2 Wind Penetration

On the basis of wind penetration, all five proposed schemes approximately double the export capacity at bus 11 compared to the 3-MW case without control. This is because the voltage and line overload problems occurring near bus 11 are not significant hence the energy lost in generation curtailment can be avoided. Consequently, the wind capacity factor at bus 11 as a result of all schemes also remains nearly identical. On the other hand, at bus 12 where the constraints are more severe the OPF-based joint management with cost Case B could yield the highest energy exports, i.e., 77.8% increase from that of the case without control, and bringing in the greatest wind capacity factor while the least energy output is due to the same scheme when the DG bus 11 is assigned the cheapest cost (only 49.3% increase from without control case). This scheme also causes the lowest wind capacity factor (i.e., 0.36 averaged over the year). This dictates that the power output is significantly curtailed to satisfy the voltage and line capacity limits as a result of the optimised solution. This is a particularly important indication that inappropriate access rules which favour less suitable sites can seriously affect overall energy harvesting with the result that simpler schemes appear to deliver better performance. The coordinated joint management delivers the second highest energy exports (73.25% greater than the case without control) while the decentralised schemes both with and without adopting the operational windows approach are comparable in terms of the wind capacity factor.

### 6.5.3 System Losses and Reactive Power Exchanges

In terms of the system energy losses, it is apparent that the larger wind capacity connected the more system losses occurred. All schemes result in an almost similar amount of system losses. The OPF-based scheme with cost Case B causes the smallest energy losses and the second lowest energy losses occur when the OPF-based scheme with cost Case C and the coordinated joint management are employed.

Reactive power exchanges are required by the wind farm bus 12 in all schemes but only the non-optimisation ones present the need for power factor adjustment at bus 11. The non-OPF schemes mainly operate the wind farms inductively to mitigate the voltage rise problems. On the other hand, the OPF-based schemes require the wind farm bus 12 to operate with capacitive power factor (i.e., injecting reactive power into the system). As seen, a large amount of reactive power injection is required possibly in order to provide voltage support elsewhere in the systems due to voltage regulation from the OLTC transformers.

Currently in the UK, there is no clear policy or legislative incentive for DG in providing voltage control and reactive power compensation in place. However, the issue regarding the role of reactive power support and charging for DG units has been of concern. In [130], it is suggested that DG in agree to utilise the power factor capability to support distribution network voltages and would be charged for consuming reactive power that exceeds the agreed level. In Germany and Spain, for instance, the legislative frameworks for wind integration state the requirements regarding voltage control and supply of reactive power: in Germany new wind plants are required to provide both services and in Spain wind farms are incentivised to supply reactive power and receive up to 8% bonus based on a reference tariff (78.4 €/MWh in 2010) [131]. With such frameworks being made comprehensive and clear, this could potentially encourage DG to participate in active management and could be seen as an extra economic benefit gained, e.g., through rewards for voltage mitigation and incentives for the wind farms (DG units) that utilise the active management schemes.

### 6.5.4 Economic Viability Evaluation

In this subsection, the economic feasibility of each proposed scheme is evaluated based on the cost break-down provided in Table 6 - 5. The information and figures are approximates based on the author's judgement and are published in [95, 132, 133]. In reality, there may be various costs and/or benefits beyond those presented here and must be taken into account. For instance, speed of deployment compared to network reinforcement and performance improvement of network constraints could be accounted for as additional benefits whereas standardisation and replication of the scheme's hardware and logic could be regarded as cost due to a lack of technological readiness and commercialised deployment at the current stage. Additional benefits from current incentives to DG and DNOs, e.g., Low Carbon Network Fund (LCNF), DG incentive scheme, treatment of opex and capex, losses incentive scheme, etc., are also not considered in this analysis. More information can be found in [57, 102, 134].

**Table 6 - 5: Costs and revenue break-down**

| Categories | Cost | Unit |
|---|---|---|
| **Wind Farm Costs** | | |
| Wind farm capital cost | 750,000 | £/MW |
| Network connection cost | 150,000 | £ |
| **Active Network Management Costs** | | |
| DG control box and local hardware (applies to all) | 20,000 | £/DG |
| Digital radio link (point to point), (whole lifespan) | 20,000 | £/link |
| Dedicated phone line communications/pilot wires (whole lifespan) | 120,000 | £/line |
| Measurement IED units (voltage, current, etc., distributed installation) | 20,000 | £/unit |
| DMS controller (regional substation) | 200,000 | £/unit |
| **Revenues** | | |
| Approximate Renewable Certificate and energy market unit price | 60 | £/MWh |
| **Additional Benefits** | | |
| Carbon dioxide offset | 0.499 | tonne$CO_2$/MWh |
| Carbon dioxide offset price | 10 | £/tonne $CO_2$ |

The economic evaluation is also based on the following assumptions: wind turbine lifespan is 20 years for the wind farm at buses 11 and 12; the discount rate of 10% is used to estimate the net present value (NPV) and gives rise to an annuity factor of 8.51 which is used to convert annual cash flows into the present value of the wind farms' revenues over the lifespan.

In estimating the cost and revenue of a scheme, it is important to clarify the scheme's ownership as this affects the cost and revenue categories (Table 6 - 5) and to whom the costs would be charged and who would benefit from the revenues. In reality, the economic feasibility of the scheme may be evaluated based on whether the DG is owned by a developer or the DNO and whether the DG is already connected. This affects matters such as Distribution Use of System (DUoS) charges and the scheme cost. Other associated costs may also be required, e.g., metering charges, top-up and standby charges and network reinforcement if it is not covered in the connection charges [135]. To avoid the specifics between the DG developer and the DNO and to obtain the overall economic feasibility, the evaluation has been carried out from the societal point of view by assuming that: the wind farm and the control scheme are to be built hence all cost components are required; the OPEX and O&M for the wind farms are modest; and the active management schemes' OPEX are low. The active network management capital costs are speculative but assumed reasonable and selected to differentiate between the decentralised and centralised functions.

In defining the active management scheme cost, each decentralised, coordinated and centralised management scheme requires different sets of technologies. The scheme components' cost break-down used in this evaluation is provided in Table 6 - 6. The DG controller and local hardware installation are applied to all wind farm, one control box per wind farm (assuming that the costs for feasibility study, software and hardware installation, computer setup for online data monitoring and acquisition, sensitivity analysis and IT and administration are inclusive). Additional communication technologies, i.e., digital radio link and dedicated phone line, are required for the coordinated and centralised management schemes to allow necessary coordination between the control room, substation and wind farms. In addition to this, the optimisation-based scheme would require wide-area measurement units and regional distribution management system (DMS) controller to support data transfer and acquisition of the entire network. For the 12-bus distribution network it is assumed that one measurement unit per bus was installed, i.e., 10 units in total.

**Table 6 - 6: Component requirement for each control scheme**

| Schemes → Categories ↓ | No control | V&T Mgt | V&T Mgt OW | Coordinated V&T Mgt OW | OPF-based V&T Mgt TAP cost Case B | OPF-based V&T Mgt TAP cost Case C |
|---|---|---|---|---|---|---|
| DG controller | No | 2 | 2 | 2 | 2 | 2 |
| Digital radio link (point to point) | No | No | No | 1 | 3 | 3 |
| Dedicated phone line | No | No | No | 1 | 3 | 3 |
| Measurements (IED units) | No | No | No | No | 10 | 10 |
| DMS controller | No | No | No | No | 1 | 1 |

The economic evaluation of each scheme is carried out using the following equations:

***Wind farm***

$$\textit{Lifetime energy export} = \textit{Annual energy export} \times \textit{lifespan} \quad (6 - 7)$$

$$\textit{Annual energy sales/ROCs} = \textit{Annual energy export} \times \textit{ROCs and energy price} \quad (6 - 8)$$

$$\textit{PV of lifetime sales/ROCs} = \textit{Annual sales/ROCs} \times \textit{Annuity factor} \quad (6 - 9)$$

$$\textit{PV of lifetime } CO_2 \textit{ offset} = (\textit{Annual } CO_2 \textit{ avoided}) \times \textit{Annuity factor} \times CO_2 \textit{ offset price} \quad (6 - 10)$$

$$\textit{PV of total revenues} = \textit{PV of lifetime sales/ROCs} + \textit{PV of lifetime } CO_2 \textit{ offset} \quad (6 - 11)$$

$$\textit{Total wind farm cost} = \textit{Wind farm CAPEX} + \textit{Connection cost} \quad (6 - 12)$$

$$NPV_{WF} = \textit{PV of total revenues} - \textit{Total wind farm cost} \quad (6 - 13)$$

***Whole network***

$$NPV_{Network} = \textit{Total } NPV_{WF} + \textit{Total cost of scheme} \quad (6 - 14)$$

$$\textit{Levelised cost} = \frac{\textit{Total costs of wind farm and control scheme}}{(\textit{Annual energy exports} \times \textit{Annuity factor})} \quad (6 - 15)$$

**Evaluated Results**

The estimated costs and revenues for wind farm buses 11 and 12 and the whole network according to the proposed schemes are presented in Table 6 - 7 to Table 6 - 9, respectively. The results reveal that based on NPV gained at bus 11 over the lifetime all schemes are comparable (with an increase by more than double of without control) as a result of low severity of constraints except the lowest incurred by using the OPF-based scheme (cost Case B which favours production at bus 12) due to the scheme's optimal active power dispatch (£362,678 lost in curtailment over the lifetime). The cost of the Case B scheme however allows the highest NPV at bus 12, i.e., 70% increase from the 3-MW case without control, whereas the same operating system but different favoured wind farm (case C) yields the lowest NPV (only 25.82% increase from without control). This is caused by a great volume of active power dispatch resulting in the highest opportunity costs (around £3.2m lost in curtailment).

**Table 6 - 7: Estimated costs and revenues for wind farm bus 11**

| Schemes → Bus 11 Categories ↓ | No control | V&T Mgt | V&T Mgt OW | Coordinated V&T Mgt OW | OPF-based V&T Mgt TAP cost Case B | OPF-based V&T Mgt TAP cost Case C |
|---|---|---|---|---|---|---|
| **Total wind farm costs** | 2,400,000 | 4,650,000 | 4,650,000 | 4,650,000 | 4,650,000 | 4,650,000 |
| **Wind farm revenues and benefits** | | | | | | |
| Energy export (MWh) | 10,800 | 21,710 | 21,700 | 21,710 | 21,000 | 21,710 |
| Annual energy sales/ROCs (£) | 648,000 | 1,302,600 | 1,302,000 | 1,302,600 | 1,260,000 | 1,302,600 |
| Lifetime energy export (MWh) | 216,000 | 434,200 | 434,000 | 434,200 | 420,000 | 434,200 |
| Present value of lifetime Sales/ROCs (£) | 5,516,789 | 11,089,768 | 11,084,660 | 11,089,768 | 10,727,090 | 11,089,768 |
| Lifetime $CO_2$ offset (tonne) | 107,784 | 216,666 | 216,566 | 216,666 | 209,580 | 216,666 |
| Present value of lifetime $CO_2$ offset (£) | 458,813 | 922,299 | 921,874 | 922,299 | 892,136 | 922,299 |
| Present value of total revenues (£) | 5,975,602 | 12,012,067 | 12,006,534 | 12,012,067 | 11,619,227 | 12,012,067 |
| **NPV (£)** | **3,575,602** | **7,362,067** | **7,356,534** | **7,362,067** | **6,969,227** | **7,362,067** |
| **Opportunity costs (energy lost in curtailment)** | | | | | | |
| Annual energy lost (MWh) | N/A | 0 | 10 | 0 | 710 | 0 |
| Lifetime energy lost (MWh) | N/A | 0 | 200 | 0 | 14,200 | 0 |
| Present value of lifetime curtailed generation (£) | N/A | 0 | 5,108 | 0 | 362,678 | 0 |

**Table 6 - 8: Estimated costs and revenues for wind farm bus 12**

| Schemes → Bus 12 Categories ↓ | No control | V&T Mgt | V&T Mgt OW | Coordinated V&T Mgt OW | OPF-based V&T Mgt TAP cost Case B | OPF-based V&T Mgt TAP cost Case C |
|---|---|---|---|---|---|---|
| **Total wind farm costs** | 2,400,000 | 4,650,000 | 4,650,000 | 4,650,000 | 4,650,000 | 4,650,000 |
| **Wind farm revenues and benefits** | | | | | | |
| Energy export (MWh) | 12,600 | 21,690 | 21,530 | 21,830 | 22,400 | 18,800 |
| Annual energy sales/ROCs (£) | 756,000 | 1,301,400 | 1,291,800 | 1,309,800 | 1,344,000 | 1,128,000 |
| Lifetime energy export (MWh) | 252,000 | 433,800 | 430,600 | 436,600 | 448,000 | 376,000 |
| Present value of lifetime Sales/ROCs (£) | 6,436,254 | 11,079,552 | 10,997,822 | 11,151,066 | 11,442,230 | 9,603,300 |
| Lifetime $CO_2$ offset (tonne) | 125,748 | 216,466 | 214,869 | 217,863 | 223,552 | 187,624 |
| Present value of lifetime $CO_2$ offset (£) | 535,282 | 921,449 | 914,652 | 927,397 | 951,612 | 798,674 |
| Present value of total revenues (£) | 6,971,536 | 12,001,001 | 11,912,474 | 12,078,463 | 12,393,842 | 10,401,974 |
| **NPV (£)** | **4,571,536** | **7,351,001** | **7,262,474** | **7,428,463** | **7,743,842** | **5,751,974** |
| **Opportunity costs (energy lost in curtailment)** | | | | | | |
| Annual energy lost (MWh) | N/A | 3,540 | 3,700 | 3,400 | 2,830 | 6,430 |
| Lifetime energy lost (MWh) | N/A | 70,800 | 74,000 | 68,000 | 56,600 | 128,600 |
| Present value of lifetime curtailed generation (£) | N/A | 1,808,281 | 1,890,011 | 1,736,767 | 1,445,603 | 3,284,533 |

**Table 6 - 9: Estimated costs and revenues for the whole network**

| Schemes → <br> Whole Network Categories ↓ | No control | V&T Mgt | V&T Mgt OW | Coordinated V&T Mgt OW | OPF-based V&T Mgt TAP cost Case B | OPF-based V&T Mgt TAP cost Case C |
|---|---|---|---|---|---|---|
| Control system costs (£) | N/A | 40,000 | 40,000 | 180,000 | 860,000 | 860,000 |
| Wind farm costs (£) | 4,800,000 | 9,300,000 | 9,300,000 | 9,300,000 | 9,300,000 | 9,300,000 |
| Present value of lifetime revenues (£) | 12,947,138 | 24,013,068 | 23,919,008 | 24,090,530 | 24,013,068 | 22,414,041 |
| NPV (£) | **8,147,138** | **14,673,068** | **14,579,008** | **14,610,530** | **13,853,068** | **12,254,041** |
| Present value of lifetime curtailed generation (£) | N/A | 1,808,281 | 1,895,119 | 1,736,767 | 1,808,281 | 3,284,533 |
| Levelised cost (£/MWh) | 24.1 | 25.3 | 25.4 | 25.6 | 27.5 | 29.5 |

From the societal viewpoint of the whole network, it is important to note the NPV against the overall (wind farm and scheme) costs and the levelised costs for each scheme, as represented in Figure 6 - 16. Despite providing the most effective voltage and thermal constraints mitigations, the OPF-based scheme offers the lowest NPV and results in the most expensive overall costs incurred by the requirements for measurement, communication and optimisation technologies (around 9% more expensive than the total costs of the decentralised scheme). The optimal solutions also yield the most expensive levelised cost, around £5.3/MWh more expensive than the energy cost for 3-MW plant without control. Of all schemes, the decentralised management offers the highest NPV, with approximately 80% increase in the NPV compared to without control. The choice for wind farm' export to be encouraged, dictated by the 'fuel' cost as presented earlier, also has an effect on the NPV and the levelised cost of energy. Making the 'wrong' choice over which wind farm to favour in producing higher exports could bring about more expensive energy cost and therefore losing the NPV that would have been obtained: the levelised cost for Case C is around £2/MWh more expensive resulting in a loss of 11.5% NPV compared to the cost Case B.

Given that the scheme costs (communication, measurement and DMS units) presented here are speculative, additional tests for varying the ROCs/energy price and the communication, measurement and DMS costs have been made. Raising the energy price by 50% had a large impact on the overall NPV (increased by around 1.5 times for all schemes) whereas reducing the price by half caused a great drop in the NPV for all schemes. A 50% increase in the costs for communication, measurement and DMS caused a loss in the NPV of the OPF-based scheme (cost Case C) by around 3% and increased the levelised cost by £1.1. If those technologies were cheaper (e.g., due to future advanced development), the NPV would be improved which would lower the levelised cost by around 50 pence/MWh.

According to the results, it can be inferred that achieving flexibility, extendability and optimality in the active network management may not truly be the most economically viable choice, at least not in the short term. The OPF-based schemes provide superior constraints management performance, the economic feasibility could be seen as a barrier compared to the decentralised approach where the performance may be sufficiently effective at more economic investment. In saying that DNO regulations do not allow overvoltages and overloading therefore at present the OPF approach may be the only allowable option. To some extent a decision on allowing overvoltage and overloading require a cost to be attributed to them. In essence the difference between the OPF NPV and that of the other schemes offers one such measure of the value of accurate compliance with the voltage and capacity limits.

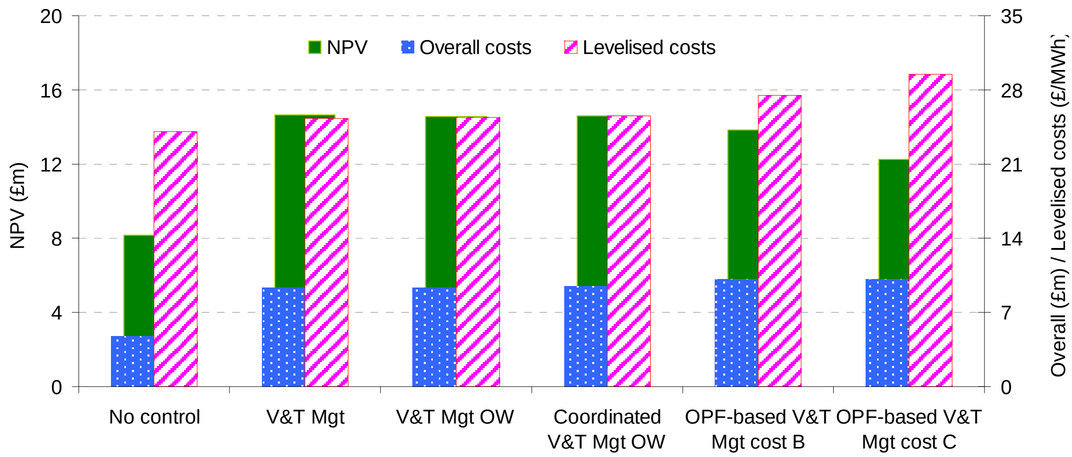



**Figure 6 - 16: Comparisons of NPV (£m) against overall (£m) and levelised (£/MWh) costs of the whole network for each scheme**

It is enlightening to consider at this stage the alternative approach to active network management to connect both wind farms (12-MW total). The traditional options would include re-conductoring or constructing a new line in parallel to the line 10-12. The cost of an overhead line typically ranges between £50-100/m [136]. If a new line between buses 10 and 12 (33km long) were to be constructed, the lowest cost incurred would equate £1.65 million. This, by nearly double, outweighs the total scheme cost of the most expensive OPF-based scheme.

The economic evaluation presented here is only an estimated framework as part of the proposed active management's showcases. The cost break-down values and elements may overestimate the actual ones (as it is not the main purpose of this thesis) however the outcomes are expected to provide useful information for DNOs, DG developers and researchers. Thorough analysis with actual specifics for a scheme to be implemented as well as a comparison with the traditional network reinforcement solution would be required.

### 6.5.5 Risks and Benefits

Following on from Table 4 - 7 in Chapter 4, the overall risks and benefits of the five proposed schemes are summarised in Table 6 - 10.

**Table 6 - 10: Risks and benefits comparison of the proposed schemes**

| Schemes | Benefits/Advantages | Risks/Disadvantages |
|---|---|---|
| V&T Mgt | • Effective voltage rise and thermal overload mitigation<br>• Simplicity of method<br>• More economically viable and shorter payback period due to reduced capital investment compared to coordinated management approach<br>• Speed of deployment benefit<br>• Extendability (up to certain degree of network topology) | • Voltage management limited by reactive power capability, size and type of a generator and DNOs requirement<br>• Sensitivity calculation errors<br>• Reduced performance in larger and more complex network with diverse DG connections<br>• Require coordination principles for multiple DG units |
| V&T Mgt OW | • Effective voltage rise and thermal overload mitigation<br>• Simplicity of method<br>• More economically viable and shorter payback period due to reduced capital investment compared to coordinated management approach<br>• Speed of deployment benefit<br>• Extendability (up to certain degree of network topology) | • Voltage management limited by reactive power capability, size and type of a generator and DNOs requirement<br>• Sensitivity calculation errors<br>• Reduced performance in larger and more complex network with diverse DG connections<br>• Require coordination principles for multiple DG units |

| | | |
|---|---|---|
| Coordinated V&T Mgt OW TAP | • Improved voltage control performance from OLTC support<br>• Effective thermal overload mitigation<br>• Reduce the need for generation curtailment in voltage management<br>• Speed of deployment benefit<br>• Flexibility and extendability to other DG units with similar management method as communication between units can be made available | • Sensitivity calculation errors<br>• Require coordination principles for multiple DG units<br>• Loss of communication is an issue as operation relies on communication between DG and OLTC<br>• Thermal management performance may be reduced due to delay in coordinated OLTC mechanism |
| OPF-based V&T Mgt | • Optimal solutions providing perfect constraint management performance<br>• Offer flexibility and extendability of active management to more DG units and larger and more complex network with smart-grid based technologies | • Although providing most effective constraints mitigation, energy lost in generation curtailment is relatively large (cost Case C)<br>• Loss of communication and measurement/optimisation system failure are an issue as operation heavily relies on robustness and reliability of measurement, optimisation and communication technologies<br>• Capital investment may be an issue for implementation<br>• Speed of deployment disadvantage due to complicated scheme arrangement and methodology<br>• Longer payback period due to high upfront costs |

Considering the common achievement in providing real-time management of voltage and line capacity constraints, nonetheless, each proposed scheme yields different degree of risks and benefits that might satisfy network operation in one manner but not another. Such contradictory outcomes require thorough evaluation as to which scheme offers the most suitable benefits if it is to be implemented. Based on the author’s experience in developing the active management schemes over the past years, there are a number of factors associated with risks and benefits that need to be taken into account. The influencing factors are:

- Network topology including type and size of network, sensitivity of network to constraints, operating voltage levels, any existing control and demand size and characteristics;

- Availability and reliability of communication, measurement and optimisation technologies;
- Resource variability and capacity of DG units;
- Actual capacity factor of DG;
- Ability to provide active and reactive power from DG if to participate in one of the proposed schemes;
- Priority arrangement for multiple DG units;
- Operational objectives and preferences from DNOs and DG developers;
- Fuel cost and energy price;
- Benchmark of DG in providing voltage support.

## 6.6 Chapter Six Summary

From the decentralised scheme(s), the degree of coordination has been extended by adding a simple coordination rule between the local voltage management and the available OLTC transformer voltage regulation using direct communication link. Progressing towards some degree of coordination in the local-only control strategy allows the distribution networks an opportunity to expand the use of emerging innovative technologies and accommodate greater amount of DG capacity.

To signify a perfect situation, the OPF tool integrated in PSS/E is employed with the preference to maximise the wind DG exports under the voltage and thermal constraints. The optimisation scheme presents a smart grid based management that extends a higher degree of coordination and communication. The performance of the OPF application in managing constraints has been demonstrated in a number of case studies. When the optimisation tool is fully deployed, it offers the most successful solution against both constraints. As the objective of optimisation is to minimise the overall fuel costs, the control actions mainly attempt to restrict the wind power output which leads to a reduction in the energy exports. The results present significant evidence that while the best control performance is gained the energy lost in the constraining actions is also large which decreases the energy exports. Such trade-off may be balanced or negotiated by means of an agreement between the DNOs and DG developers that must consider not only the performance to manage constraints but also economic feasibility of a scheme in order to achieve the most appropriate framework. Justification on the basis of risks and benefits of the proposed schemes is also significant and requires thorough evaluation considering the most influential factors.

# Chapter 7

# Discussion and Conclusions

## 7.1 Introduction

This final chapter summarises the key findings and discusses the main aspects, the contributions to knowledge and the limitations of the methods that have arisen throughout this thesis. Lastly, potential progression and future work are outlined and recommendations are proposed.

## 7.2 Chapter Summary

Six chapters have been presented in this thesis. The principal messages are summarised as follows:

Chapter 1 structured the thesis with its research background and motivations where the hypothesis and objectives and scopes of this research were stated. An overview of the research methodology together with the main contributions and deliverables were also given. Finally, it listed all associated published work that was produced throughout this research.

Chapter 2 detailed the main subjects regarding distributed and renewable generation, drivers, DG technologies, potential development in the UK, and distribution networks focusing on the integration of DG. Several technical impacts as a result of DG connections onto the networks were highlighted including voltage rise and line thermal overload. The chapter also informed readers of the concept of smart distribution network and its significance of which a detailed explanation followed in Chapter 3.

Chapter 3 covered the fundamentals of active (smart) distribution networks and identified three approaches along the active management spectrum based on their control, communications and optimisation characteristics: decentralised, semi-coordinated and centralised control. The former formed the core contribution of this research with the other two subsequently modelled for comparison. Comprehensive reviews of relevant research and development and existing technologies in the area of active network management followed with a focus on active voltage and line flows management. The potential benefits and risks of active management were also highlighted. At the end, the concept of Smart Grids and the related activities in the UK, Europe and US were introduced.

Chapter 4 established the decentralised voltage and thermal management schemes using a series of sophisticated methods developed throughout this research. It began with providing a background review of the decentralised voltage control developed in a key piece of prior art from which this research was considerably extended to utilise active power curtailment and simultaneous management of thermal overload constraints in real-time. The operation and the corresponding control settings were explained. Time-series simulations demonstrating the control mechanisms for individual voltage and thermal management schemes and joint operation were presented. For different methods, the setting options were investigated. Full case studies of the decentralised schemes were presented for a more realistic distribution network model and the performance was assessed.

Chapter 5 further enhanced the decentralised voltage and thermal management using an operational windows approach to improve the effectiveness in capturing the voltage and thermal constraints. The detailed concept and operation were explained. Again, the developed approach was demonstrated to show the control operation over voltage and line flow problems, followed by a case study.

Chapter 6 delivered the final part of this research programme by implementing new coordination and centralised optimisation methods with which to compare the performance of the decentralised control methods described in chapters 4 and 5. Firstly, it extended the decentralised voltage and thermal management to coordinate with the OLTC voltage regulation. Then, an OPF-based tool was employed to reveal the performance of optimal control and operation. The performance was also compared with the non-optimisation schemes to differentiate the strengths and weaknesses. Validations of both and case studies were presented. Finally, the overall performance of the key developed schemes was discussed with the economic viability of the schemes clearly evaluated.

## 7.3 Discussion of Schemes and Key Results

Voltage rise and line overload are two of the most significant and commonly found problems in distribution networks connected with DG, particularly variable generation. This thesis has concentrated on tackling the variability of wind that affects the voltage at the point of connection and the line overload adjacent to it in order to allow the maximum wind connection. The developed schemes aim to overcome both constraints simultaneously and in real-time. The control schemes have been classified into three approaches along the active management spectrum: decentralised, semi-coordinated and centralised control.

**Decentralised Voltage and Thermal Management**

The individual voltage and thermal management schemes have been developed by employing reactive power control (for voltage management) and active power curtailment (for thermal management but also as a last resort for voltage management) with a series of sophisticated concepts. For both, the reduction rate enforced time delay and sensitivity analysis have been exploited. The validation results have revealed that the sensitivity analysis provides superior and more precise operation in tackling the constraints. The scheme employing this method has been further extended in the joint voltage and thermal management which was able to effectively provide corrective actions against the voltage rise and line overload constraints in real-time. The ability to handle both constraint types and the avoidance of errors associated with fixed sensitivity factors differentiates it from existing active distribution network management approaches.

**Operational Windows Approach**

The operational windows approach can improve the control capability to capture and identify the situations ranging from less to very severe voltage and/or line thermal flows exceeding the thresholds and accordingly the statutory limits. The threshold, target, time delay and holding time values were applied as a means to perform precise and appropriate corrective actions. It also offers DNOs and DG developers a compromise scenario in a way that the tuneable settings could permit the highest possible returns in energy exports while ensuring the security of network operation.

The process of selecting the control parameters would be fairly straightforward given that there are only a small set of threshold and target values. It would need to be seen to operate across a wide range of credible circumstances and with tolerable error. Less conservative settings would promote enhanced production but increase risk of overloads and over-voltages. These settings are influenced by: the DNO's tolerance of transient over-voltages and overloads; the expected rate of change of wind and demand between time-steps; whether short-term forecasts are applied; and the speed of OLTC operation. It is expected that an automated routine could be developed to 'optimise' the parameters perhaps on a multi-criteria basis.

**Coordinated Voltage and Thermal Management**

Provided that communication between the DG unit and substation can be made available, the voltage and thermal management coordinated OLTC scheme has been developed using a simple coordination concept where the OLTC assists the decentralised scheme to overcome the voltage rise. Tests have been carried out and the results have illustrated improved performance over voltage constraint. It is also revealed that with the coordination the need for generation curtailment in voltage management reduces which allows more power export.

**OPF-based Voltage and Thermal Management**

The optimisation scheme presents a near-smart grid based management method that extends a higher degree of coordination and communication. The performance of the OPF application in managing constraints has been demonstrated in a number of case studies. The results revealed that with the optimisation tool being fully deployed, it offered the most successful solution against both constraints. However, as the objective of optimisation was to minimise the overall fuel costs, the control actions mainly attempted to limit the wind power output which led to a reduction in the energy exports.

Despite providing the most effective voltage and thermal constraints mitigations, the OPF-based scheme offers the worst economic viability amongst the other developed schemes. This was due to the upfront costs of measurement, communication and optimisation technologies. On the other hand, the decentralised management scheme was the most economic as it did not require those centralised technologies. However, some tolerance of minor overvoltage and line overloading may be necessary, although further development on optimal settings would minimise these impacts. The results also indicate that allowing flexibility, extendability and optimality in active network management systems may not be the most economically viable choice, at least not in the short term. While the OPF-based schemes provided superior constraints management performance, the higher upfront costs could be seen as a barrier compared to the decentralised approach where the performance may be sufficiently effective at more economic investment.

The choice of favouring the production from one wind farm over another was shown to have an effect on their economic viability. Making the ‘wrong’ choice over which wind farm to favour in producing higher exports could bring about more expensive energy cost and therefore losing the benefit that would have been obtained. This has implications for the implementation of active network schemes which operate on priority access rules.

**Influence of Forecasting**

Forecasting of demand and wind in this context has an influence on the control performance. A perfect forecast enables more precise control over both voltage and line overload constraints compared to the persistence case. Such information may be difficult to obtain in a decentralised remote area. In the persistence forecast environment, the developed sensitivity analysis method for the voltage and thermal management can provide sufficient and effective control however estimation and accordingly the control actions errors exist.

## 7.4 Limitations of the Work

The utilisation of active and reactive power capabilities and the operating conditions depend on the type and size of the DG unit as well as the DNOs requirements. These are significant factors that will determine the effectiveness of the scheme to manage the constraints and the corresponding export of the DG unit. The actual calculations of the voltage and thermal sensitivities also require knowledge of the network parameters such as lines, generations and loads that are involved in the area where the DG unit is connected. Practically, such real-time observation of the network is difficult in a scheme meant to be local and decentralised. While detailed implementation and field trial of the scheme is not the main focus of this research, it is assumed that the information of the network parameters for the simulation studies is available. As for validation purposes, however, an option could be to use an equivalent circuit of the network with historic data.

The voltage and line loading sensitivity methods allow fairly precise control actions in real time. However, the local measurement and control and avoidance of direct communication with nearby DG and OLTCs may make this approach less ‘optimal’ in terms of overall integration than more ‘centralised’ approaches. The developed schemes with different settings may also be compatible with a particular network but not with others. With this in mind, a comprehensive comparison of risks and benefits particularly with field trials of different schemes would be of value to DNOs, suppliers and DG developers in planning ANM for existing or new DG connections.

Whilst this research does not fully address the issue of multiple DG units, the control interactions between DG plants and voltage regulation devices can influence the network performance and need to be defined on a case-by-case basis. Actual implementation of the scheme would be on a faster time step than in the case studies and substantially faster than the control loop of an OLTC. This can minimise unnecessary OLTC tapping action as it will sense voltage as corrected by the scheme. The broadly same approach could be applied to coordination between DG units through differentiation of their control parameters and the 'droop' characteristic provided by the sensitivity factors exploited. The DG at the most 'sensitive' site would operate at shorter time intervals than others so that most benefit will be derived from the most influential actions, with others following as required.

The coordinated OLTC scheme resulted in excessive tap operations which might reduce the transformer lifetime in the long term. For the centralised management, reliability of communication, measurement and optimisation systems are a significant issue that determines the control performance and can affect a large part of the network if such centralised system failure occurs. Its capital investment and speed of deployment are also a challenge at least in the near term compared to the decentralised management approach.

## 7.5 Concluding Remarks

In this thesis, adaptive, decentralised control schemes for active distribution networks were developed. The novel schemes provided real-time corrective actions and were able to effectively tackle voltage rise and line overload constraints that occurred simultaneously. With wind variability worsening the voltage, an operational windows approach and coordinated OLTC schemes were able to capture the severity of voltage rise (and line overload) such that the control performance was improved as well as allowing the high power exports. The decentralised schemes could be extendable and scalable with the coordinated and centralised control means. The decentralised management scheme, as being 'localised' provides a fast-to-deploy and cost-effective alternative to more complex centralised schemes that require expensive communication infrastructure and prolonged construction periods. With this advantage, it could provide a potential interim solution that can be extended into smart distribution networks.

In addition, the author believes that the understanding and lessons learned from developing a suite of active network management schemes, are a significant basis for future distribution networks that will become fully-integrated smart grids. The operational performance in real-time particularly with the use of high resolution for time-series analyses will ensure the severity and behaviour of constraints are captured and managed in a precise and effective manner. Depending on the technical characteristics of distribution networks, trial investigations of different control methods will allow the network operators to understand how well the capability and compatibility the methods can feature. Whilst the network constraints and severity vary and that the knowledge to continuously overcome every single situation in time may be difficult, advances in forecast technology together with validated methods will significantly enhance the control performance and allow new capacity of DG to be connected. Furthermore, the solution can potentially delay the investment in network reinforcement and expansion so as to accommodate significant volumes of DG. Whether the optimal, robust and readily-available control solutions are to be achieved, active network management will need to rely on real-time trials to gain maturity. A clear policy framework, standards and business readiness for active management (and smart grids) will also need to come to the forefront before full and commercial implementation.

## 7.6 Future Work and Recommendations

Recommendations and further improvements for the joint voltage and thermal management scheme and control capability that the author would have liked to consider but nevertheless was not able to contribute due to time limitations include:

- Short-term forecasting of demand and wind could allow the ability to predict the constraint characteristics ahead of time so that the corresponding preventive control could be applied;

- Specific algorithms to coordinate DG units and/or OLTC more effectively, e.g., the use of sensitivity or distance to constraint as well as principles of access to identify the priority of multiple DG units to take actions;

- Implementation of the schemes in realistic distribution network possibly with collaboration from DNOs and DG developers;
- Use of different options of communication devices and to assess the robustness and value of communications to be embedded in the decentralised, coordinated and centralised network management;
- Assessment of the effect of variable and controllable load, e.g., increasing use of electric vehicles and storage, to represent a different simulation scenario;
- Enhanced adaptability of the schemes to trials of different types of DG units, e.g., wave, tidal and solar DG;
- Development of the schemes using dynamic power flow analysis;
- Detailed economic evaluation of the schemes that includes actual capital, operation and maintenance and other associated costs;
- Extension of schemes to deal with other technical impacts, e.g., DG contribution and response to fault levels and power quality;
- Improvement of the scripted control algorithms with up-to-date versions of PSS/E and Python and to be compatible with industrial power system software currently widely used, e.g., DigSilent, IPSA and OpenDSS;
- Enhancement of the OPF-based application to perform various multi-objective optimisations and consider different ways in defining DG units' significance in accordance with the Principles of Access.

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# Appendices

## A.1 Appendix A: Network Data, Demand and Wind Profiles

In this appendix, the network data for the 12-bus 132/33kV rural distribution system and the Scottish demand and wind profiles for 2003 used in the analyses are provided.

### A.1.1 12-Bus 132/33kV Rural Distribution Network

Network parameters of the modified 12-bus 132/33kV rural distribution network are given in Table A - 1. The original network consists of 16 buses and a voltage regulator between buses 8 and 9. The network used in the simulations has been modified by reducing buses 13 to 16 and replacing the single voltage regulator with a transmission line to allow voltage control actions from the proposed schemes.

**Table A - 1: Network data for 12-bus 33kV rural distribution network [120]**

| From bus | To bus | Line R (pu) | Line X (pu) | Rating (MVA) |
|---|---|---|---|---|
| 2 | 3 | 0.198 | 0.446 | 25 |
| 2 | 4 | 0.187 | 0.299 | 45 |
| 3 | 4 | 0.216 | 0.287 | 20 |
| 4 | 5 | 0.0305 | 0.029 | 40 |
| 4 | 6 | 0.517 | 0.376 | 15 |
| 4 | 8 | 0.441 | 0.392 | 15 |
| 6 | 7 | 0.394 | 0.348 | 15 |
| 8 | 9 | 0.0728 | 0.1039 | 15 |
| 9 | 10 | 0.538 | 0.733 | 15 |
| 10 | 11 | 0.07812 | 0.02924 | 10 |
| 10 | 12 | 0.09754 | 0.07001 | 7.5 |
| 11 | 12 | 1.888 | 1.314 | 8 |

### A.1.2 Demand and Wind Profiles in 2003

Demand and wind generation data in Scotland in 2003 used the case studies are shown in Figure A - 1. The data were obtained from [119].

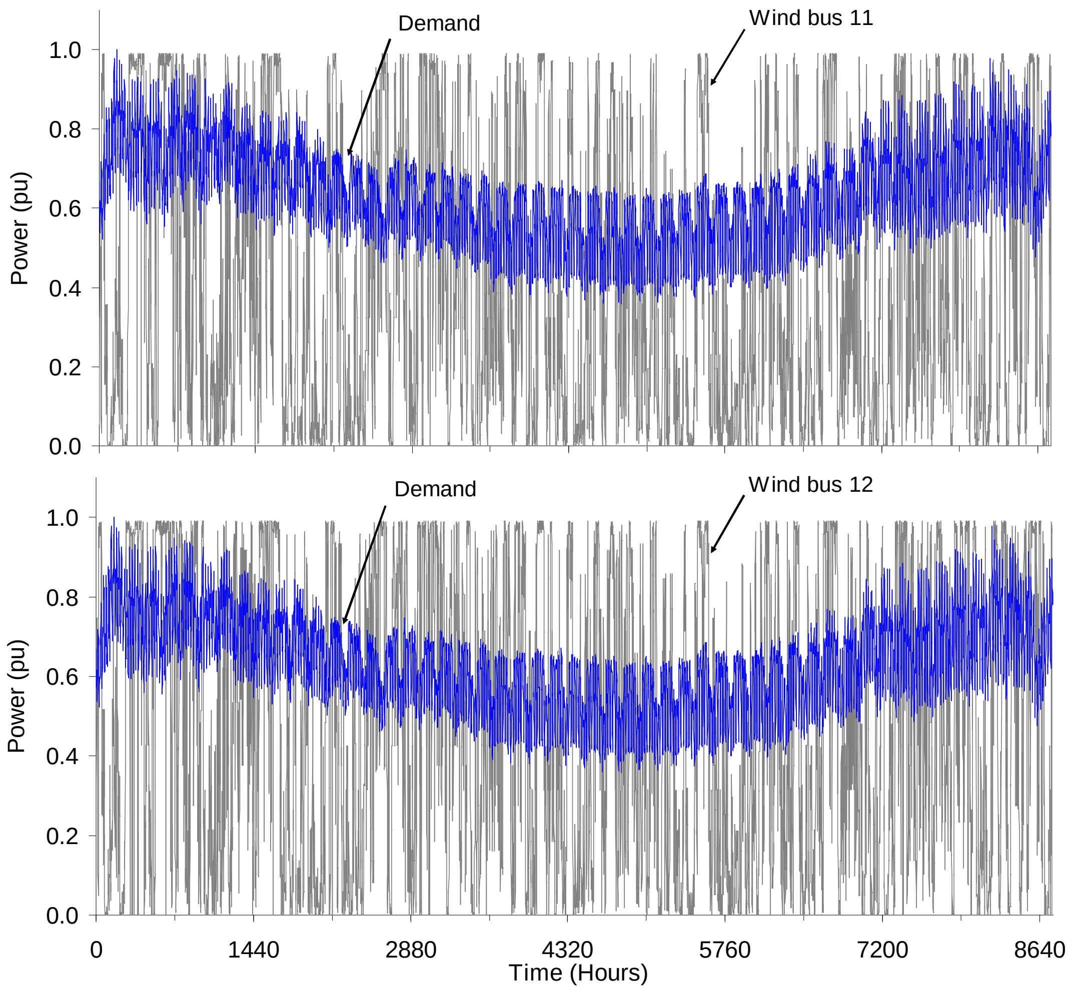


**Figure A - 1: Demand and wind generation profiles in 2003**

# A.2 Appendix B: PSS/E and Python Executed Simulation Environment

In this appendix, an overview of PSS/E software interfaced with Python scripting language which is the main simulation environment system of this research is presented. The main aspects OPF application built-in PSS/E software used in the studies is also provided.

## A.2.1 Simulation Environment Structure

Figure A - 2 shows the simulation environment structure of this research. All simulation cases have been carried out using PSS/E as the main simulation software. The control algorithms and the network models presented in this research have been scripted based on an Object-Oriented Programming (OOP) concept using Python[1] and are automated through PSS/E. Each component in a distribution system, i.e., line, transformer, bus, voltage regulation, load and generator, is modelled as a ‘class’ in Python language where the same type of objects are represented by a class. For instance, a ‘bus class’ consists of every bus in the system that is built as a ‘bus object’ and each bus is denoted normally by its bus number. In this way, modification or assignment to the data of each component can be attained. The developed control schemes are also modelled as a class, i.e., a ‘decentralised control scheme class’ consisting of many objects for each control method. For implementation, the control scheme object is interfaced with the associated object, in this case a generator object, to perform an assigned control action, e.g., modifying active and/or reactive power as required.

The simulation cases have been performed on a minute-by-minute time series basis. In each time step a power flow is solved in PSS/E. The results are generated and stored in .txt format. Analyses and graphical results are produced using Excel and Origin.

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[1] Additional detail can be found in the following book:
M. Lutz, “Powerful Object-Oriented Programming: Learning Python”, O’Reilly Media, Inc., 3rd Edition, CA, 2007.

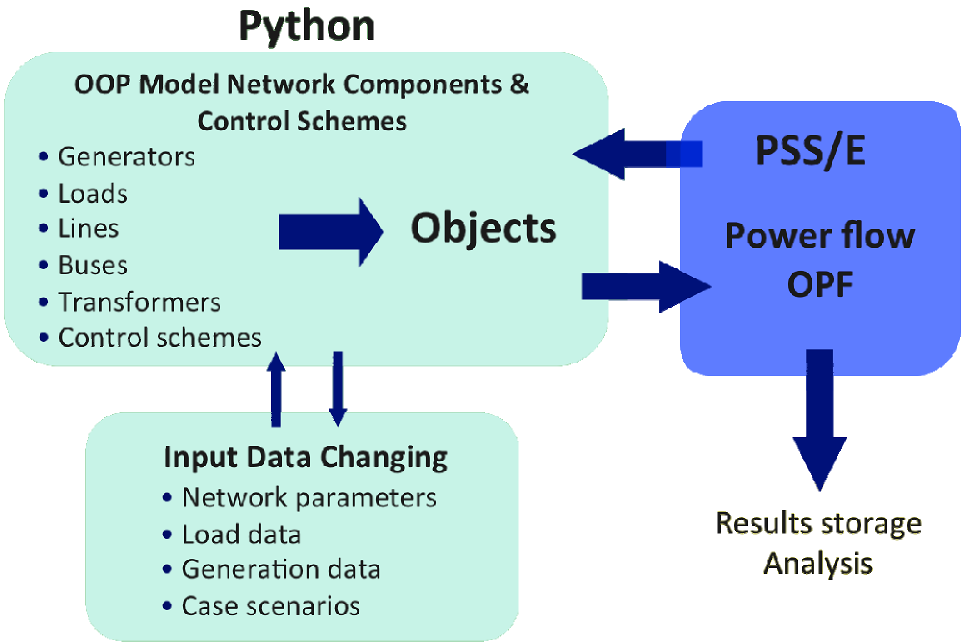


**Figure A - 2: Simulation environment platform for PSS/E automated Python**

### A.2.2 Automated Python Files

The PSS/E automated Python platform employed in this research was previously developed at the University of Edinburgh [116]. This research extends the existing materials to establish the active control schemes to mitigate voltage rise and line overload in distribution networks.

### A.2.3 Optimal Power Flow

In implementing the built-in OPF tool through PSS/E, the following data files are required [117]:

- load flow data model, i.e., PSS/E Saved Case (*.sav) or PSS/E Load flow Raw Data File (*.raw);
- OPF raw data file (*.rop);
- OPF spreadsheet and data tables;
- Objectives and solution parameter settings.

The constraint and control data necessary for the OPF platform simulated in this thesis include: Generator Dispatch Data, Bus Voltage Constraint Data and Branch Flow Constraint Data. The Generator Dispatch Data stores the reference data that are used in the dispatch. The reference data comprise Active Power Dispatch Tables which in turn references Cost Curves. In Active Power Flow Dispatch Table, table number, maximum and minimum active power generation, fuel cost scale and cost curve type are manually-assigned. Bus Voltage Constraint Data records bus number and normal maximum and minimum voltages. Branch Flow Constraint Data records specified upper and lower flow limits. The In this research, these data are input line-by-line in Python file and are executed via PSS/E continuously (in time-series) in order to search for an optimal solution for each time step. The objective functions are to minimise the overall fuel cost and active power slack bus. An option for setting a tap ratio fixed is used to keep the current (or specified) tap ratio in order to allow voltage control of other devices to take action. The readers may find additional information in [117]. The following Python syntaxes are used:

**Constraint and control data**

- psspy.opf_apdsp_tbl
- psspy.opf_gendsp_indv
- psspy.opf_bus_indv
- psspy.opf_brflw_brn_indv

**OPF objective functions and execution**

- psspy.opf_fix_tap_ratios
- psspy.opf_minimize_fuel_cost
- psspy.opf_minimize_p_slack
- psspy.nopf(0,1)

## A.3 Appendix C: Internship Project – Harmonic Assessment of Skegness Distribution Network

This appendix gives a summary of the project report delivered as an outcome of the internship at E.ON New Build & Technology Limited (formerly E.ON Engineering) from January to February 2010 (6 weeks). This internship project was financially supported by the Supergen FlexNet Consortium. The published report is a copyright of E.ON New Build & Technology Limited; accordingly, the details and results are not permitted to be included in this thesis. Should the readers wish to obtain additional explanation of this project, they could contact the author directly.

The project was to carry out an impact assessment of harmonic distortions within Skegness 33kV distribution network as a result of the connection of new wind farms and replacement of certain cable circuits by overhead lines within Skegness network. Wind turbines employing power electronic converters and the re-configuration can affect the harmonic impedances within the area. As a result, high harmonic distortions at the point of connection and nearby locations may occur and required to be assessed.

The harmonic emission levels are to be in compliance with Stage 3 of Engineering Recommendation G5/4-1. The study, performed using IPSA software, considered the network under normal and possible severe N-1 contingencies. Part of the results revealed that there was a risk of voltage distortions exceeding the planning levels which were caused either by harmonic current emissions from wind turbines or the relatively low planning levels at high harmonic even orders that might not be applicable for the connection of wind generation.

## A.4 Appendix D: Publications

This section gives the author's publications in full. All works are progressive outcomes throughout the time of this PhD. The journal and conference publications are provided in a chronological order.

**Journal Publication**

1. T. Sansawatt, L. F. Ochoa, and G. P. Harrison, "Smart Decentralized Control of DG for Voltage and Thermal Constraint Management," *IEEE Transactions on Power Systems*, In press.

**Conference Papers**

2. T. Sansawatt, J. B. O'Donnell, L. F. Ochoa, and G. P. Harrison, "Decentralised Voltage Control for Active Distribution Networks," presented at *44th International Universities' Power Engineering Conference (UPEC 2009),* Glasgow, 2009.

3. T. Sansawatt, L. F. Ochoa, and G. P. Harrison, "Decentralised voltage and thermal management to enable more distributed generation connection," presented at *CIRED Workshop*, Lyon, 2010.

4. T. Sansawatt, L. F. Ochoa, and G. P. Harrison, "Integrating distributed generation using decentralised voltage regulation," presented at *IEEE Power and Energy Society General Meeting (IEEE PES GM 2010)*, Minneapolis, USA, 2010.

5. T. Sansawatt, L. F. Ochoa, and G. P. Harrison, "Operational Windows for Decentralized Control of Renewable DG: Techno-Economic Trade-offs," presented at *IEEE Power and Energy Society Innovative Smart Grid Technologies Europe (IEEE PES ISGT Europe 2011),* Manchester, 2011.